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A PRELIMINARY STUDY
of a
SATELLITE AIDED VEHICLE AVOIDANCE SYSTEM
(SAVAS)

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ELECTRONICS RESEARCH CENTER
Cambridge, Massachusetts

THE MITRE CORPORATION

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SATELLITE AIDED VEHICLE AVOIDANCE SYSTEM

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by

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SECTION 1
INTRODUCTION

As modern aircraft became larger, faster and more numerous, the need for an effective airborne collision avoidance system to back up the air traffic control system has become more and more urgent. One need only consider the number of collisions and near-collisions to see why a sense of urgency has now permeated all levels of agencies and organizations interested in and responsible for air safety.

The history of collision avoidance development since the early 1950's can be summarized in a list of systems and techniques that have been tried and found wanting, usually on technical grounds. These past attempts have now culminated in the channeling of almost all present day effort toward the development of a new system, the so called Time-Frequency System, which shows promise of overcoming many of the problems that beset the collision avoidance systems proposed in the past.

However, the effectiveness of the Time-Frequency system cannot be judged on a purely technical basis. Economic and operational factors such as the high initial cost to the aircraft operator and the complexity of airborne equipment that is often difficult to maintain could inhibit universal acceptance of the system and thus destroy its effectiveness by limiting the number of equipped aircraft to those whose operators can afford the installation. This drawback is recognized generally, and it is to be expected that proposals for improved systems will be made from time to time.

This report records the results of a preliminary investigation of the technical feasibility of one such proposal — the SAVAS concept — which has

been advanced by NASA's Electronics Research Center of Cambridge, Massachusetts. An overall description of the proposed system appears in Section 2 of the report.

To assess the feasibility of the concept, both the theoretical and equipment aspects of SAVAS have been considered. The system theory has been studied in detail, with emphasis placed on operational usage, and a number of system problems have been identified that will require further conceptual development. System operation is discussed in Section 3. In the equipment area, an extensive review has been made of possible techniques for implementing the SAVAS system. Preliminary design alternatives and component values have been developed to clarify the equipment problems and to provide a sense of the amount and complexity of equipment required. This work is described in Sections 4 and 5.

The general findings from these studies has been that a number of very formidable development problems must be resolved in order for the SAVAS concept to attain operational candidacy. The detailed study conclusions, and recommendations on priorities in future work are discussed in Section 6.

The investigation was carried out at the MITRE Corporation, Bedford, Massachusetts, under Contract No. NAS 12-2078.

SECTION 2

REVIEW OF SATELLITE AIDED VEHICLE AVOIDANCE SYSTEM (SAVAS)

The fundamental feature of the SAVAS system is the use of a signal from a satellite to synchronize a responding signal from each aircraft. Upon receipt of the signal from the satellite, each aircraft initiates a clock and a receiving gate with the minimum possible delay and, at the same time, transmits a responding signal. Each aircraft then receives the responding signal of all other aircraft within its range and measures the time delay of each of these signals with respect to the starting time of its clock and receiving gate, and also measures the rate of change of time delay. These two parameters are then processed in a way which permits a decision as to the existence or non-existance of a hazard of collision.

2.1 THE TWO-FREQUENCY SYSTEM

The two-frequency SAVAS system is the basic configuration. In this system, the satellite transmits a periodic signal at a frequency, f_1. The transmission may be in the form of a pulse train modulated on a carrier of frequency, f_1, or any other modulation which will mark off equal intervals of time. Although further investigation will probably disclose an optimum rate for this transmission, for expository purposes, it can be assumed that the time interval lies somewhere between one and five milliseconds.

As each pulse, or mark, is received by an equipped aircraft, a receiving gate and a clock are started and allowed to run for an interval which can be made either fixed or adjustable. At the same time that the gate and clock are initiated, the aircraft emits a signal at a frequency, f_2. The f_2 signal serves two purposes: it permits the measurement of

a time delay in all other aircraft which receive the f_2 signal, and it provides a vehicle for the exchange of certain essential information between aircraft.

In each cycle or period of transmission, each equipped aircraft receives the f_1 transmission from the satellite first, followed by the responding f_2 signals from all other aircraft in its neighborhood. It then proceeds to measure the time delay between each f_2 signal received and the beginning of its receiving gate. Assuming negligible delays in the equipment, these time delays are equivalent to the delays between each f_2 signal and the f_1 signal which initiated the receiving gate. Each time delay, T, between an f_2 signal and the f_1 signal, defines an ellipsoid of revolution with the satellite at one focus and the receiving, or protected aircraft at the other.

In addition to measuring the time delay, T, for each received f_2 signal, the protected aircraft also measures the rate of change of delay, $\dot{T}$. These two measurements are then processed in accordance with a set of logical rules to determine whether a hazard of collision exists. If it is determined that a hazard exists, one or both aircraft are commanded to perform an evasive maneuver, an ascent or descent, in accordance with operational doctrine.

The logical rules used to determine the existance of a hazard are based on the assumption that all aircraft involved are moving in straight lines at constant speed and altitude when the measurements of T and $\dot{T}$ are made. To assure that this condition is true, means must be provided to command aircraft to cease all horizontal and vertical maneuvers before the alarm zone is reached. The first step in the alarm assessment is then to compare the relative altitude of the aircraft. This clearly requires that

information about the altitude of all intruding aircraft be available in each protected aircraft. Information can be made available via modulation on the f_2 response. If the altitude of the two aircraft differ by more than some pre-set quantity, the intruder is not considered a hazard and no further action is taken except to warn of the presence of another aircraft above or below, as the case may be. If the altitudes fall within a band determined by operational doctrine to be hazardous, the aircraft are considered to be co-altitude and further processing of the measurements of T and $\dot{T}$ is necessary to determine the possibility of a collision. Each aircraft computes the value of $T/\dot{T}$ for each co-altitude f_2 response it receives, and when this quantity falls below a pre-set constant, τ, a collision is considered imminent and one or both aircraft are commanded to take evasive action.

Since $\dot{T}$ depends on the closing speed of the two aircraft involved, a situation could arise wherein two co-altitude aircraft approach each other on slowly converging courses with very low $\dot{T}$. The value of $\dot{T}$ could then fall dangerously low while $T/\dot{T}$ remains well above the τ threshold. To prevent a collision under these circumstances, a minimum T alarm is also required.

2.2 TRANSPONDER SYSTEM USING THREE FREQUENCIES

In the brief description of the basic SAVAS configuration in the previous paragraph, it will be noted that the range, or the rate of change of range, between the protected aircraft and the intruding aircraft are not considered. The only quantities that can be measured are the time delay, T, between the receipt of the f_1 transmission from the satellite and the receipt of the f_2 transmission from the intruding aircraft, and the rate of change of time delay, $\dot{T}$. Moreover, because of the elliptical geometry,

the range associated with any value of T can vary over wide limits, particularly when the elevation angle of the satellite, as seen from the protected aircraft, is low. For example, for a satellite elevation angle of 60 degrees, the range to the intruder for a fixed time delay, T, will vary over a range of of 3 to 1, and for a satellite elevation angle of 30 degrees, the variation will be 14 to 1.

The true range between the protected aircraft and the intruder aircraft can be found by means of a system which is an extension of the basic two-frequency SAVAS configuration. In the extended system, each aircraft carries an f_1 receiver, as before, and initiates a clock and receiving gate upon receipt of the f_1 signal from the satellite and also responds with an f_2 signal. Each aircraft which receives an f_2 signal again measures the delay, T, and delay rate, $\dot{T}$, in the usual way but in this case also responds with a signal at a frequency f_3. Each aircraft must carry an f_3 receiver and, upon receipt of an f_3 signal, measures the delay and delay rate between each f_3 signal and its own f_1 signal or, equivalently, the f_2 signal. This delay now defines a spherical geometry, the f_3 delay being directly proportional to the true range to the intruder, R, and the rate of change of delay proportional to $\dot{R}$.

In a two-aircraft encounter, this basic three-frequency system will provide mutual exchange of range, range rate, and other information that can be encoded on the f_2 or f_3 responses. When more than two aircraft are in proximity however, the system is vulnerable to spurious responses. For example, in a three-aircraft situation, there will be three f_2 transmissions, each of which will evoke two f_3 responses, for a total of six. Assuming that each aircraft ignores its own f_3 responses, it will then

receive four others, only two of which are valid responses to its own f_2 interrogations, the other two being the responses of the intruding aircraft to each other.

A possible solution to this problem is the use of two f_2 responses in each aircraft. The first would again be simultaneous with the receipt of the f_1 signal from the satellite and would be used in all other aircraft to measure the delay as usual. The second f_2 response would be transmitted after a short delay which could be varied slightly from pulse to pulse. The second f_2 pulse would also initiate a second gate and clock, and the delay of any received f_3 pulse would be measured with respect to these. Of course, the f_3 transponder in each aircraft would be designed to ignore the first of the f_2 pulses and respond only to the second.

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SECTION 3

SAVAS SYSTEM OPERATION (TWO-FREQUENCY SYSTEM)

This section considers the detailed operation of the two-frequency SAVAS system that has been outlined in Section 2. Emphasis has been placed on the identification and description of a number of areas and problems needing further study.

The symbols and coordinate system used in this section are as follows (see Figure 1):

α Azimuth angle of satellite from protected aircraft

ϵ Elevation angle of satellite from protected aircraft

θ Angle between $\bar{V}_s$ and $\bar{S}$

φ Angle between $\bar{S}$ and $\bar{D}$

τ Time to projected collision

Δ Duration of each aircraft transmission

a Azimuth angle of intruder from protected aircraft

e Elevation angle of intruder from protected aircraft

h Angle of relative velocity vector (relative heading of intruder)

$\bar{D}$ Vector, $\bar{S} - \bar{R}$

$\bar{R}$ Vector, relative position of intruder

$\bar{S}$ Vector, position of satellite with respect to protected aircraft

$\bar{V}$ Vector, relative velocity of intruder

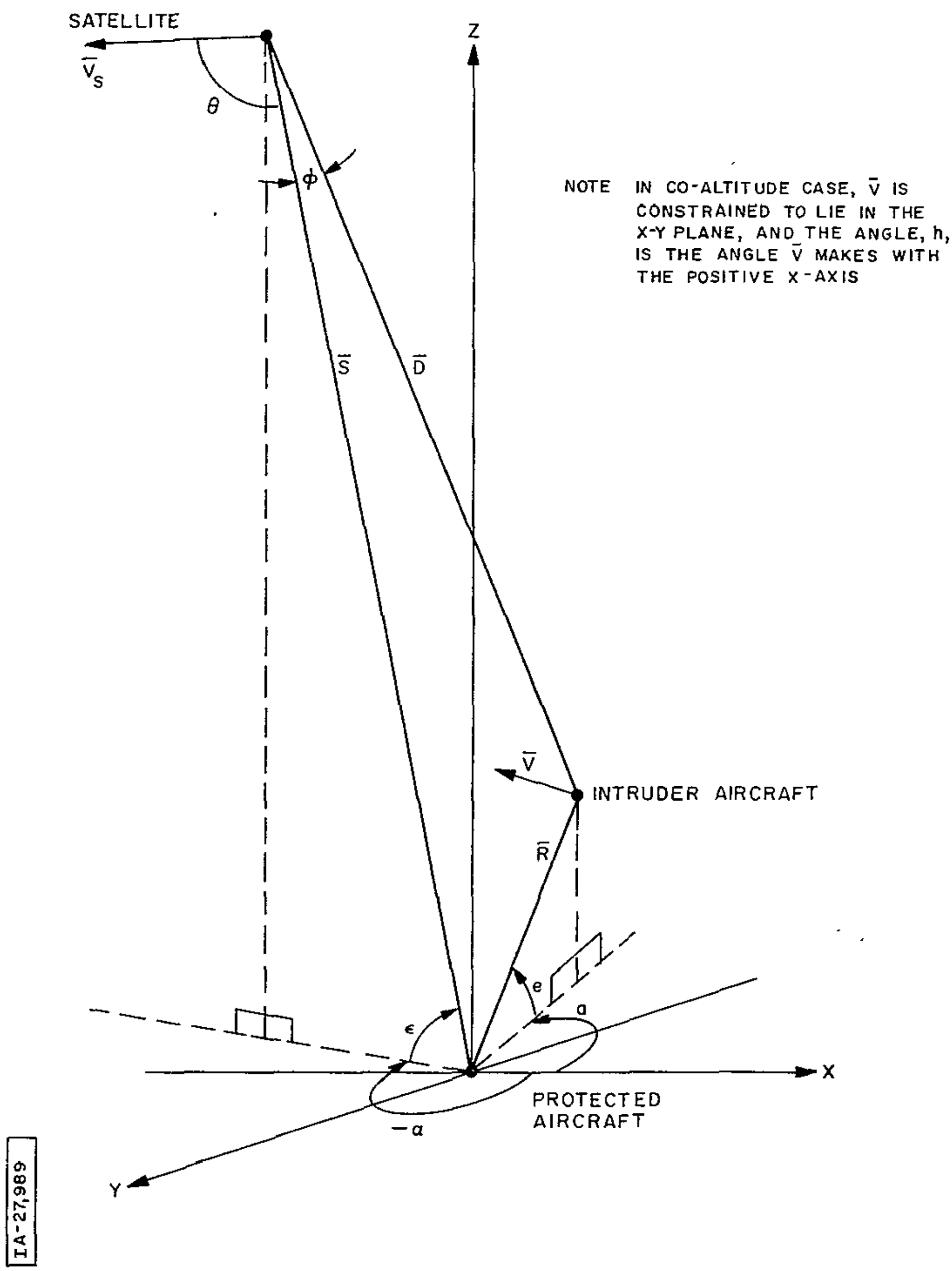

Figure 1. SAVAS Coordinate System

$\bar{V}_s$ Vector, relative velocity of satellite

D Absolute value of $\bar{D}$

R Absolute value of $\bar{R}$

S Absolute value of $\bar{S}$

V Absolute value of $\bar{V}$

V_s Absolute value of $\bar{V}_s$

T Signal delay

C Velocity of light in vacuum

i, j, k Unit vectors in a cartesian coordinate system.

Derivative of any quantity with respect to time is denoted by a dot above the quantity.

i.e., $\dot{T}$ is $\frac{dT}{dt}$, etc.

3.1 WARNING REGIONS

The SAVAS concept employs two basic warning regions: (1) alert regions, in which potentially threatening intruder aircraft must halt vertical and horizontal maneuvers, and (2) alarm regions, in which hazardous collision conditions are determined to exist and evasive action in accordance with promulgated doctrine is needed.

3.1.1 Alarm Regions

3.1.1.1 Criteria

The collision threat or alarm regions for SAVAS are determined from three sensory derived criteria: (1) $T/\dot{T}$, the quotient of signal delay

and rate of change of signal delay (i.e., the minimum time to projected collision); (2) R_{min}, the minimum proximity or slant range between aircraft; and (3) $\pm\Delta H_{max}$, the maximum altitude difference for any credible threat.

$\underline{T/\dot{T}}$

Equation (23) of Appendix I gives the co-altitude alarm zone produced by the $T/\dot{T}$ criterion as,

$$R \leq V\tau \left[\frac{\cos a - \cos \epsilon \cos \alpha}{1 - \cos \epsilon \cos (a-\alpha)} \right], \tag{1}$$

where:

ϵ = elevation angle of the satellite;

a = azimuth of the intruder aircraft;

α = azimuth angle of satellite;

T = delay between transmission of f_2 signal by protected aircraft and reception of intruder f_2 signal by protected aircraft;

$\dot{T}$ = rate of change of T;

τ = threshold value of $\frac{T}{\dot{T}}$;

i.e. $-\frac{T}{\dot{T}} \leq \tau$ denotes hazard of collision; $\dot{T} < 0, \tau > 0$.

That is, the alarm is given when this equation is true and is not given if:

$$R > V\tau \left[\frac{\cos a - \cos \epsilon \cos \alpha}{1 - \cos \epsilon \cos (a-\alpha)} \right]. \tag{2}$$

$\underline{R_{min}}$

When V is sufficiently low, R can become very small without setting off the $T/\dot{T}$ alarm. This situation arises when two aircraft at the same altitude are on slowly converging courses, and can result in R becoming small enough to produce a collision because the $T/\dot{T}$ alarm is actuated too late for evasive action. To avoid this possibility, a minimum range warning or alarm is necessary. However, since range is not directly available, a lower threshold of signal delay, T, must be established.

The co-altitude range is given by Equation (22) of Appendix I as,

$$R = \frac{C\,T}{1 - \cos\epsilon \cos\,(a - \alpha)} \tag{3}$$

where

$$C = \text{Velocity of light.}$$

If we set a minimum threshold for T,

$$R = \frac{C\,T_{min}}{1 - \cos\epsilon \cos\,(a - \alpha)}\ . \tag{4}$$

At the point where the fraction is a minimum, we have,

$$C\,T_{min} = (1 + \cos a_{min})\,R_{min}\ . \tag{5}$$

Thus, for a minimum range of 3 km and a minimum satellite elevation angle of 60 degrees,

$$T_{min} = 15 \times 10^{-6} \text{ sec.}$$

An important consequence of this quantity, T_{min}, is that the f_2 response of the protected aircraft must be completed in a time that is short compared to T_{min}, since while it is transmitting its own f_2 signal, it cannot receive the f_2 signals of intruder aircraft.

The co-altitude range at which an R_{min} warning will be given is then:

$$R = \frac{R_{min} (1 + \cos \epsilon_{min})}{1 - \cos \epsilon \cos (a - \alpha)} \tag{6}$$

where $R_{min} (1 + \cos \epsilon_{min})$ is a constant that is set by operational doctrine. A plot of the quantity:

$$\frac{1}{1 - \cos \epsilon \cos (a - \alpha)} \tag{7}$$

is shown by Figure 2 for satellite elevation angles of 30 and 60 degrees. The scales can be converted to the true co-altitude minimum warning range by multiplying by the quantity $R_{min} (1 + \cos \epsilon_{min})$. The shape and size of the figure are independent of satellite azimuth, but its major axis is always concident with the satellite azimuth. It should be noted that the minimum range warning between two aircraft is, in general, not mutual.

$|\Delta H|$

Aircraft which are sufficiently separated in altitude must not be required to maneuver since no collision hazard is present. Therefore, an

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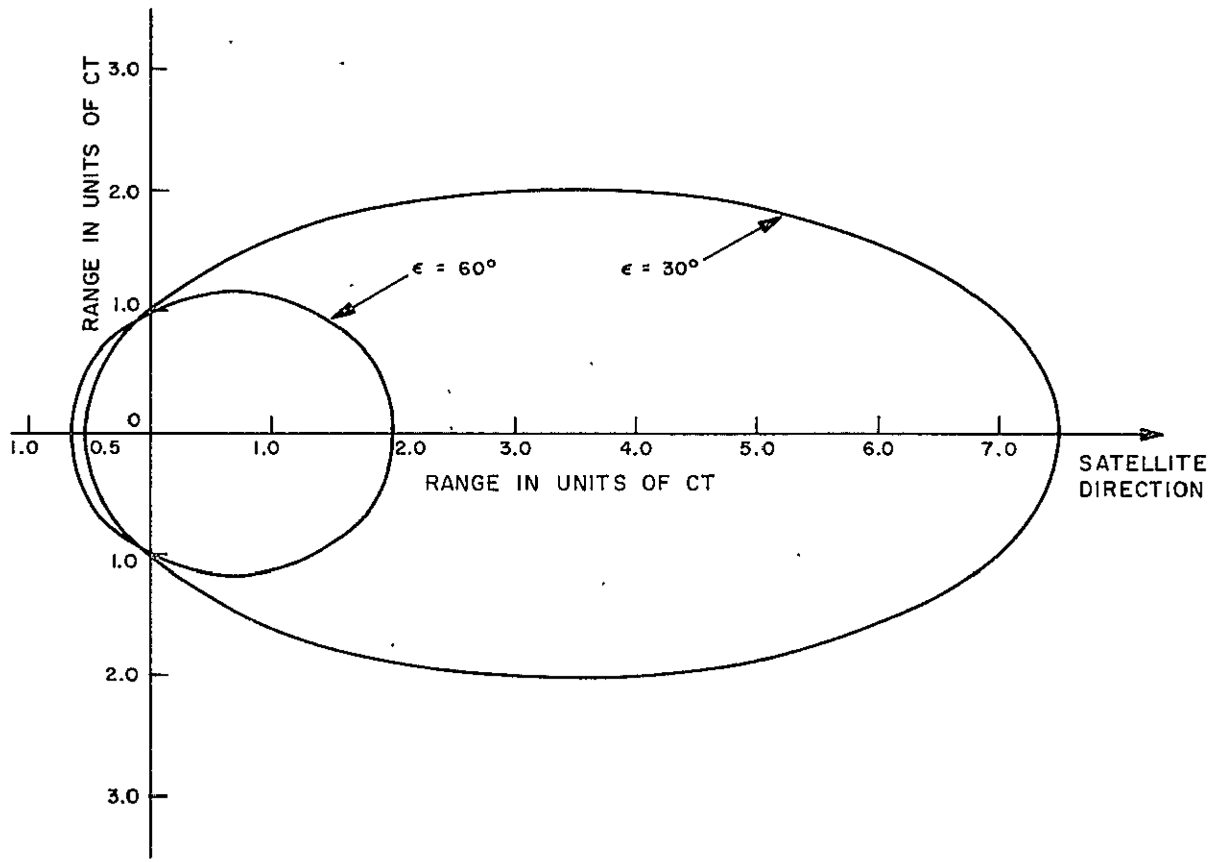

Figure 2. R_{min} Co-Altitude Alarm Region ($\alpha = 0^0$, $h = 180^0$)

additional criterion, altitude separation, is incorporated in the SAVAS concept, and each aircraft must periodically transmit its altitude by some type of coding on the f_2 transmissions.

<u>R_{max}</u>

The possibility has been considered of eliminating, by means of an R_{max} criterion, portions of the $\frac{T}{\dot{T}}$ alarm region that extend into airspace where collision hazards are not present; a fixed receiving gate would effectively establish a maximum T criterion. Thus, non-essential parts of the $(T/\dot{T})$ region, where $T > T_{max}$, could be eliminated.

Unfortunately, it is found that when a receiving gate is sized to permit reception of essential alarm data, no other part of the $(T/\dot{T})$ alarm region is eliminated. A derivation of this result is given in Appendix II.

3.1.1.2 Description of Coverage

Employing the threat evaluation logic specified in Table I, the normalized co-altitude collision alarm regions are plotted in Figures 2 through 7. In these figures, the protected aircraft has been placed at the origin, and the coordinate axes have been rotated so that the relative velocity vector of the intruder aircraft is always parallel to the horizontal axis and pointing to the left. No constraint is placed on the position of the intruder aircraft. The set of alarm regions shown in Figures 3 to 7 corresponds to the type A or C threats defined in Table I; Figure 2 is for type B threats.

Type A alarm regions for satellite angles between 180 and 360 degrees are mirror images of the regions plotted for satellite azimuths between 0 and 180 degrees. The shape of Type B alarm regions shown in Figure 2, remains constant and only the orientation of its major axis varies with changes in the position of the satellite.

Table I

Collision Threat Definitions

Credible Collision Threats	$(T/\dot{T})$ Criterion	R_{min} Criterion	$\lvert\Delta H_{max}\rvert$ Criterion
A	$(T/\dot{T}) \leq \tau$	$R > R_{min}$	$\lvert\Delta H\rvert \leq \lvert\Delta H_{max}\rvert$
B	$T/\dot{T} > \tau$	$R \leq R_{min}$	$\lvert\Delta H\rvert \leq \lvert\Delta H_{max}\rvert$
C	$T/\dot{T} \leq \tau$	$R \leq R_{min}$	$\lvert\Delta H\rvert \leq \lvert\Delta H_{max}\rvert$

The figures indicate that the SAVAS concept described in Reference [1] can provide alarm regions which give suitable collision warnings when normalized for speeds of closure and evasive action time. It should be emphasized again that the relative velocity vector is always constrainted to be horizontal and pointed to the left in these figures. For example, Figure 3 should not be interpreted to mean that intruders could approach undetected from the left; rather, if the satellite orientation is held on the positive X axis, the alarm region when the intruder relative velocity points to the right is depicted by the mirror image of Figure 7.

The calculations on which the alarm regions are based are given in Appendix I. Both the exact case and approximate equations have been programmed for computer solution. Appendix I provides quantitative data on the high accuracy of the approximate formulation when reasonable satellite distances are assumed.

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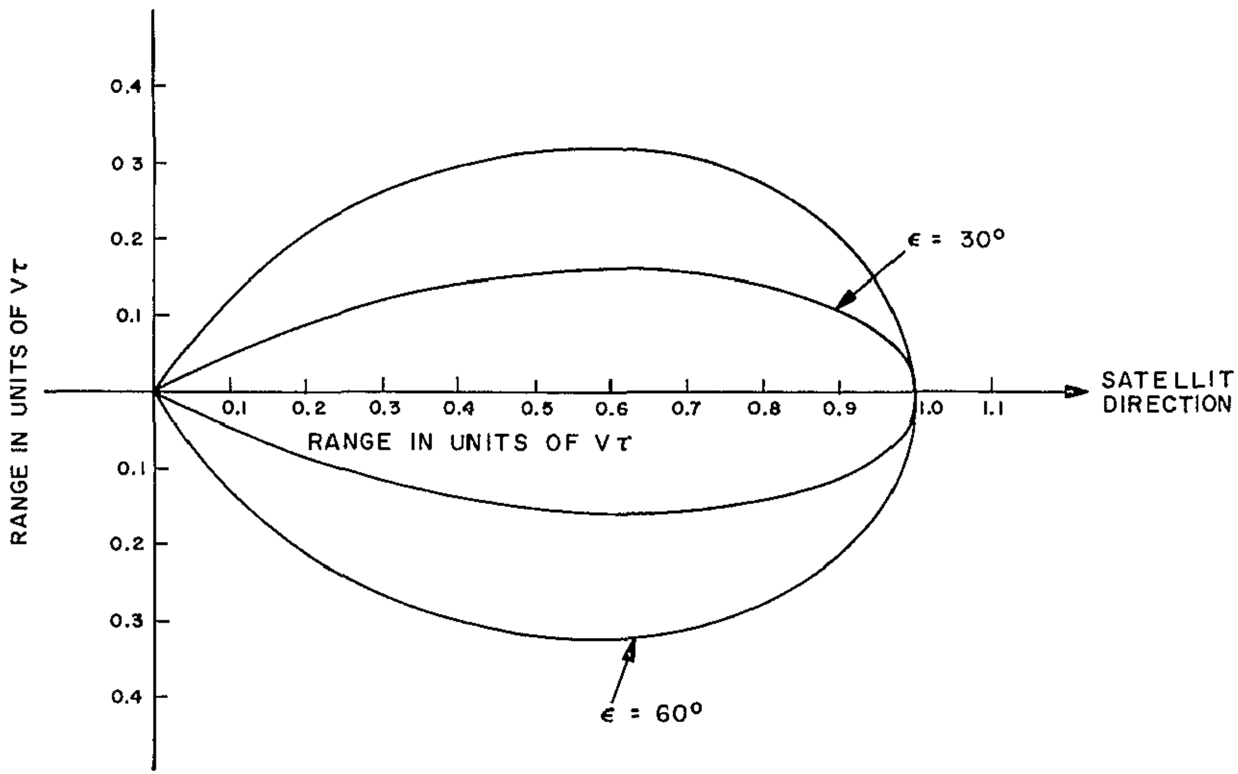

Figure 3. T/Ṫ Co-Altitude Alarm Region ($\alpha = 0^0$, h = 180^0)

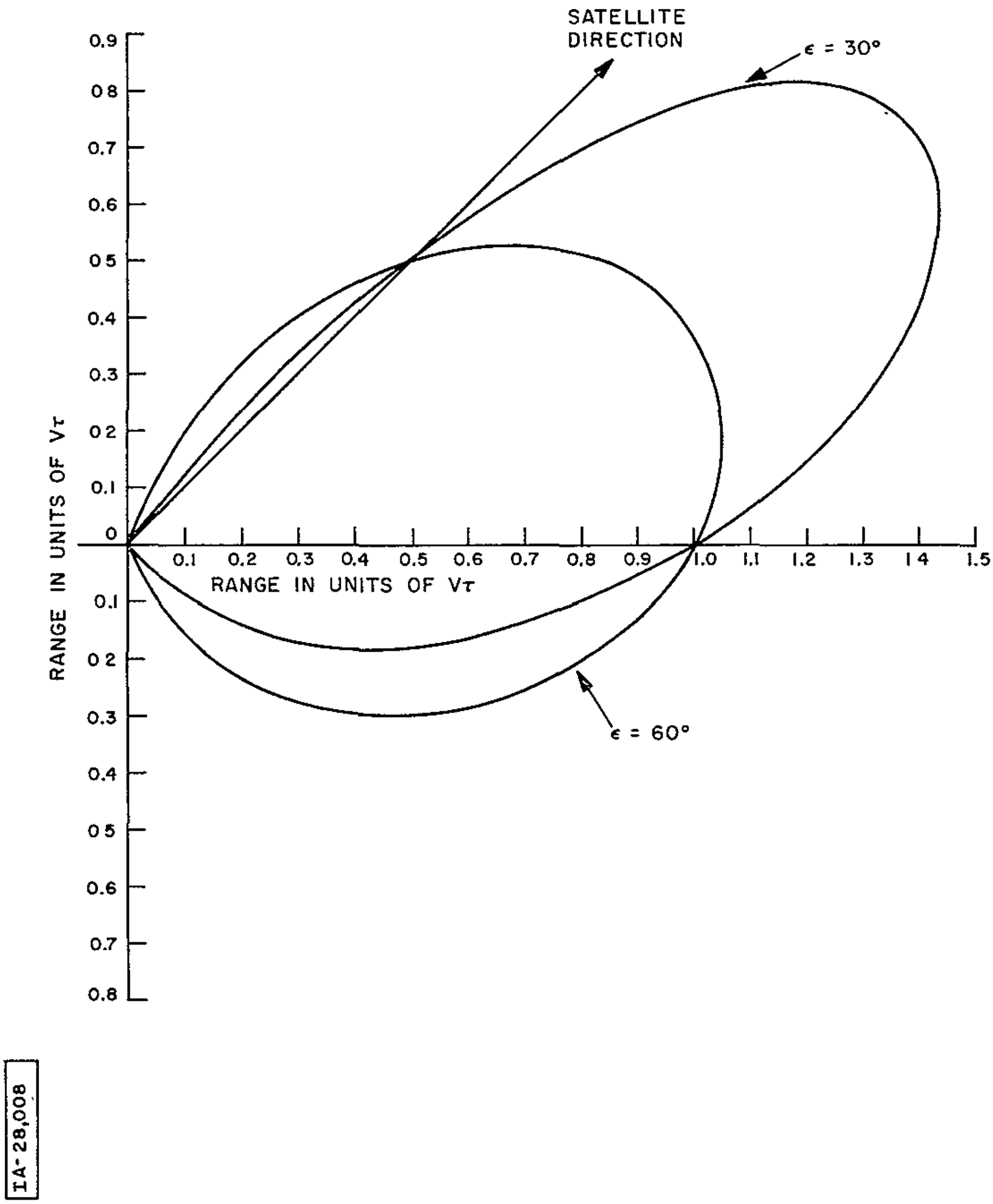

Figure 4. T/Ṫ Co-Altitude Alarm Region ($\alpha = 45^0$, h = 180^0)

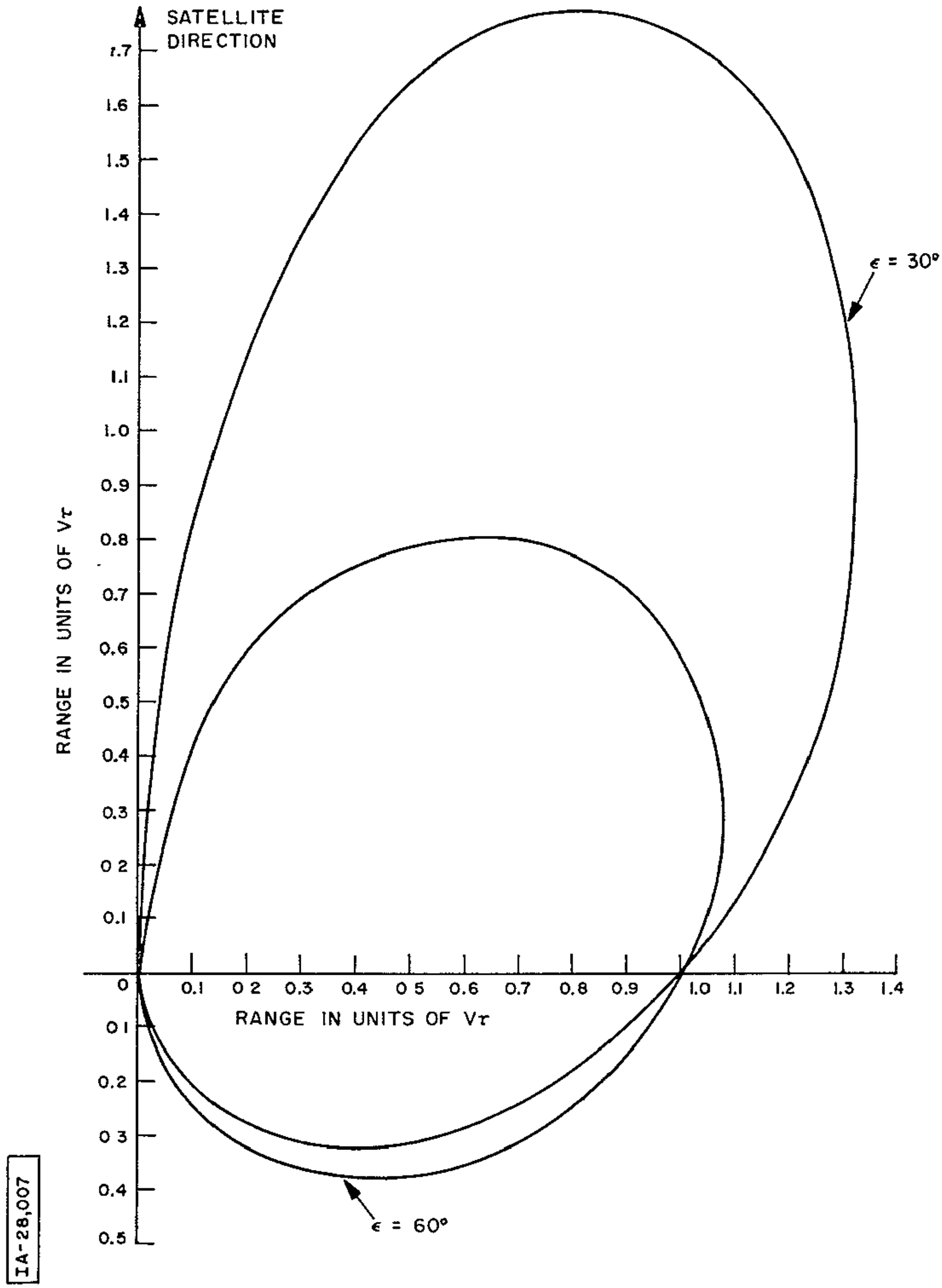

Figure 5. T/Ṫ Co-Altitude Alarm Region ($a = 90^0$, h = 180^0)

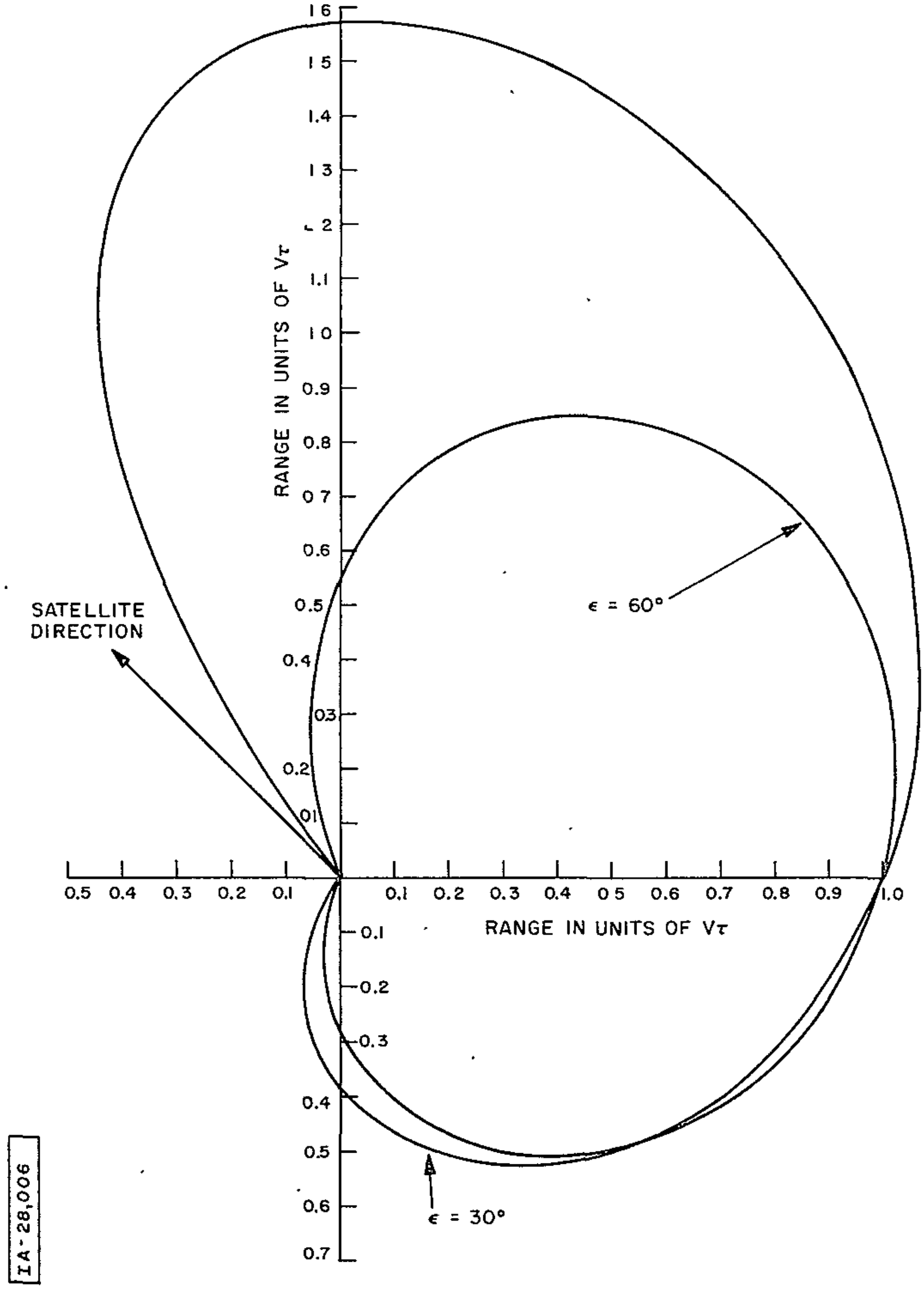

Figure 6. T/Ṫ Co-Altitude Alarm Region (a = 135^0, h = 180^0)

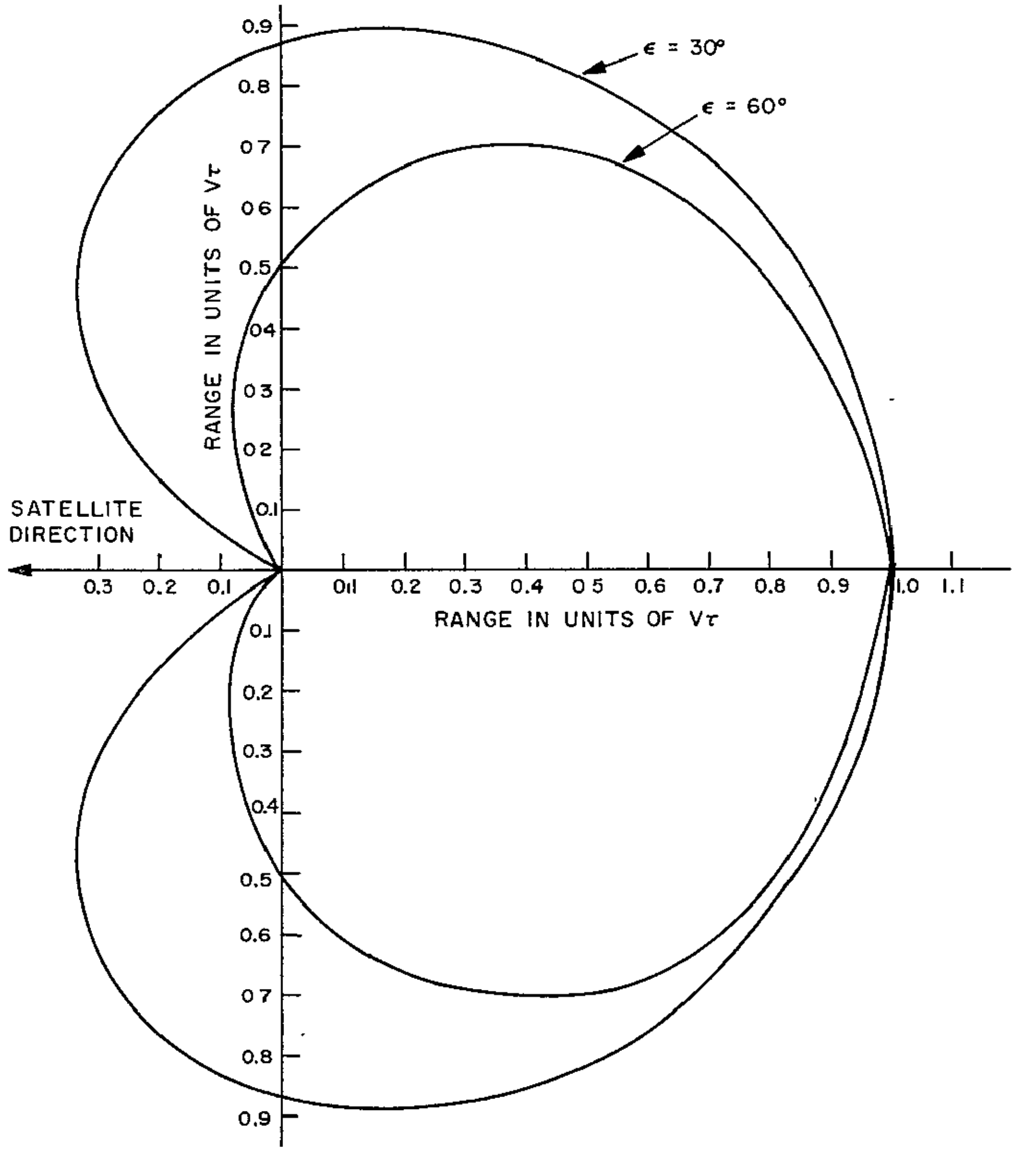

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Figure 7. T/$\dot{T}$ Co-Altitude Alarm Region (a = 180^0, h = 180^0)

3.1.1.3 Coverage Problems

Non-Reciprocal Alarm Regions - Because the satellite orientation strongly affects the $T/\dot{T}$ alarm region shape, the alarm region of the protected aircraft can differ greatly from the alarm region of the intruder aircraft. An example of this effect is shown in Figures 8 and 9, which illustrate the following points:

(a) Closing aircraft may or may not receive alarm indications simultaneously. Hence, doctrine for evasive maneuvers must consider both situations. In particular, situations in which both aircraft indicate the same altitude, and receive simultaneous alarm indications (Figure 7) cause doctrinal problems that will require careful study.

(b) The region in which either one of two closing aircraft receives an alarm can be almost double the size of the alarm region from one aircraft, and this must be taken into account in considering aircraft packing.

Satellite Elevation and Airspace Requirements - When the elevation angle of the satellite becomes low with respect to the protected aircraft, the SAVAS geometry causes the alarm regions to be extended to include considerable airspace where collision hazards are not present. This trend is shown in Figures 2 through 7. Therefore, it is desirable that the satellite orbits be designed to have the highest possible elevation angles in their regions of coverage.

3.1.2 Alert Regions

The function of the alert region is to force all intruder aircraft to attain straight, level flight prior to penetration of the collision alarm region.

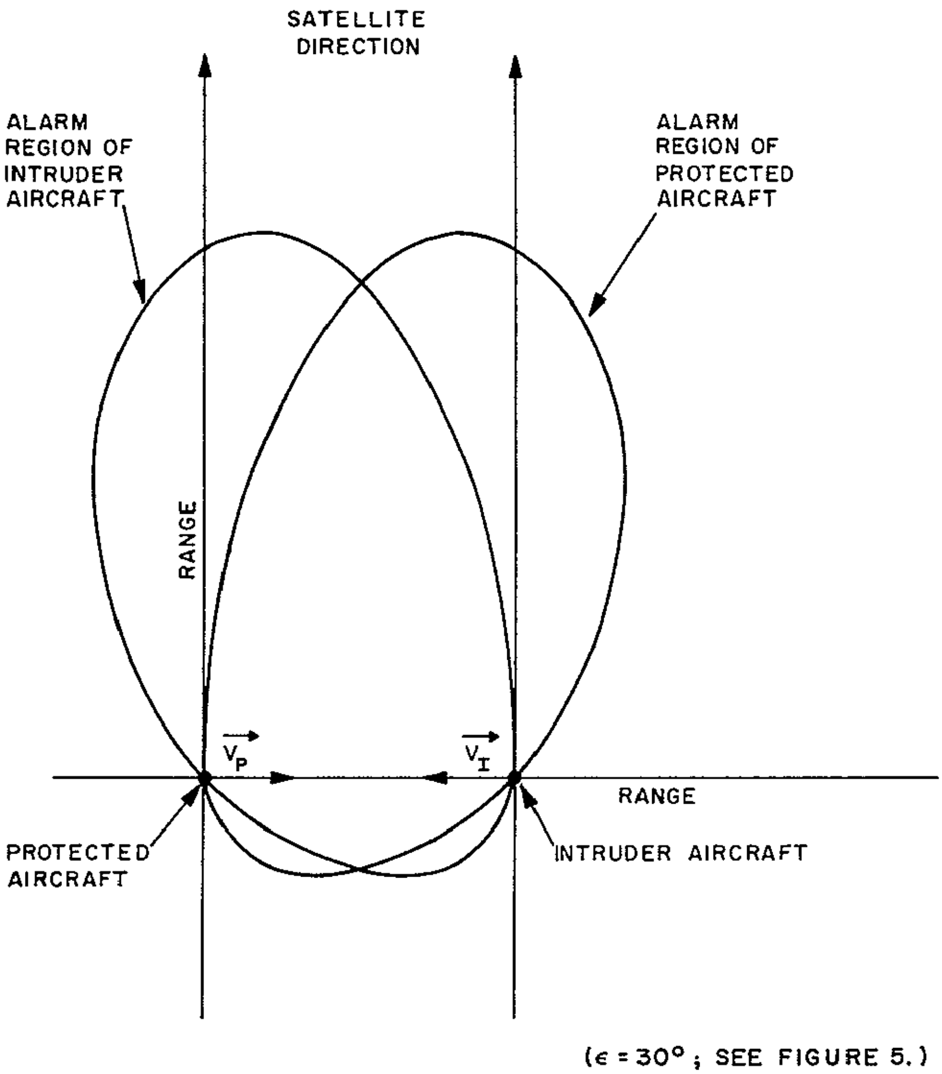

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Figure 8. Simultaneous Alarm Encounter

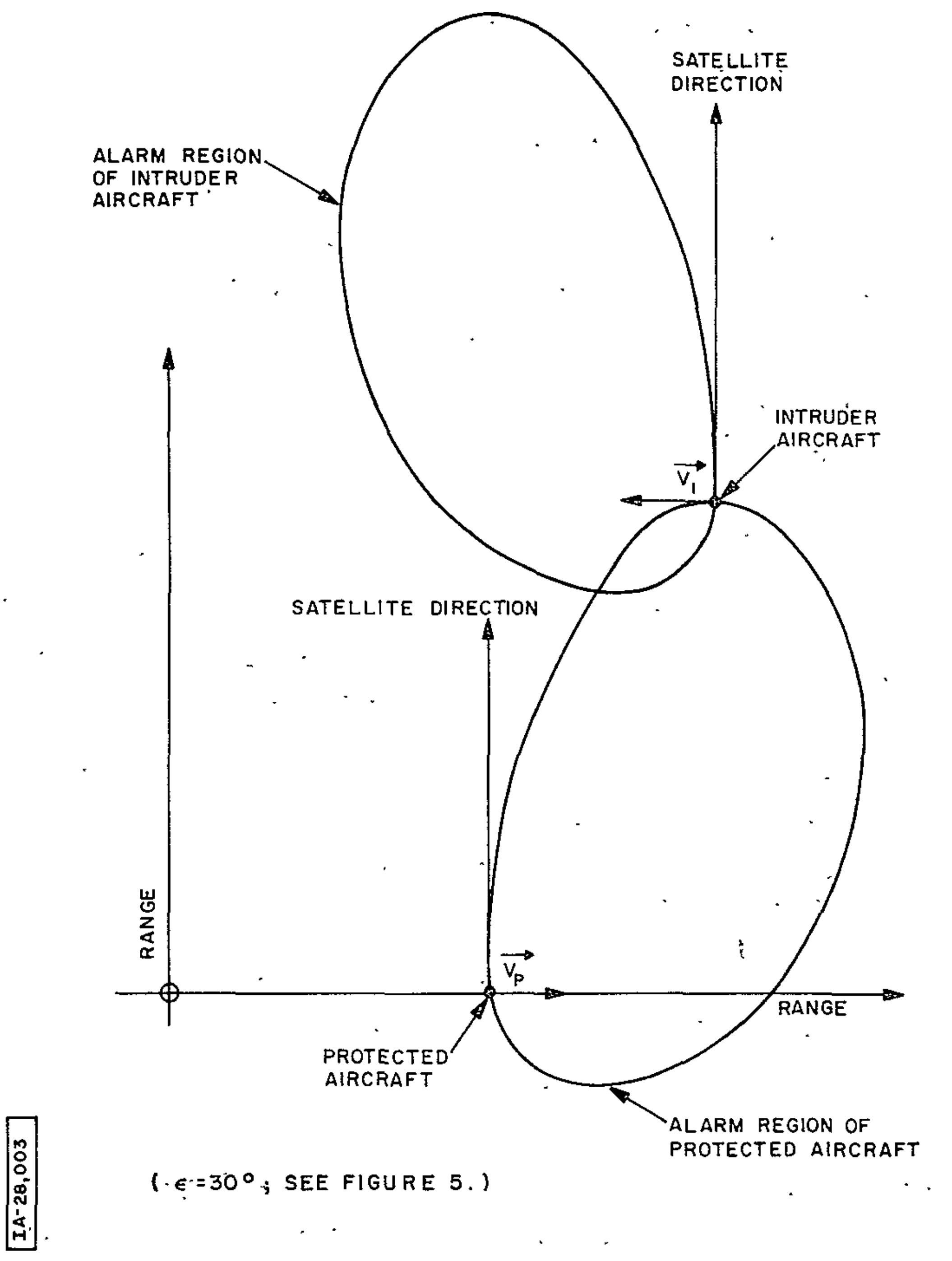

Figure 9. Single Alarm Encounter

This is necessary for the formulation of evasive maneuver doctrine, since without such knowledge it would be necessary to ascertain the intruder's course in order to avoid collision.

A number of alternatives are possible for sensing the alert regions and further investigation in this area is desirable. A basic problem, in contrast to the alarm regions, is that the alert region must be sensed by the intruder as well as by the protected aircraft since the intruder must also know that he is to terminate maneuvers.

The possiblity that the protected aircraft could determine the alert region, in a manner analagous to alarm determination, and simply communicate with the intruder does not seem promising. It would then be necessary by some means to identify and inform the intruder that his maneuvers should be halted. It is not clear, how, without extensive modification, the SAVAS concept could be utilized to direct such messages to specific intruders without affecting all the other aircraft in the vicinity.

Therefore, it shall be assumed that the intruding aircraft must be responsible for determining its own penetration of alert regions. It shall also be assumed that scaled versions of either Type A or Type B regions shall be used for sensing.

The problem of non-reciprocal regions then arises. First the alert regions must be wide enough to allow the intruder aircraft time to terminate their maneuvers before entering the alarm region of the protected aircraft. Further, the intruder aircraft do not know: (1) the specific shape of the protected aircraft alarm region, (2) the specific shape of their own alert regions or, (3) the orientation of these regions with respect to one another. Therefore, it will be necessary to determine worst case approach situations

and scale the overall alert regions so that even in the worst case, sufficient time will be available to achieve straight, level flight. Unfortunately, this may cause the overall alert region to be quite large, particularly for low satellite elevations.

3.2 MULTIPLE INTRUDER PERFORMANCE

SAVAS performance in high density traffic areas is complicated by the many geometric possibilities that exist for satellite position, intruder position and velocity vectors, and shape and orientation of the warning regions for both protected and intruder aircraft. Because of this complexity, it appears that SAVAS multiple intruder performance will ultimately be best described in statistical terms. For more detailed consideration of the problem, it will be desirable to eventually develop some systematic classification of the possible multiple intruder situations into a number of tractable categories.

In this section, several kinds of unfavorable situations are considered; other more normal situations are covered in Reference [1].

3.2.1 Situations Resulting in Reception of Overlapping Signals

3.2.1.1 Ambiguous Intruder Positions

Associated with each intruder spatial resolution cell is an ellipsoidal shell that contains all other intruder positions that will normally result in the reception of overlapping pulses at the protected aircraft. The cause of the overlap is that the total of the satellite-to-intruder distance and the intruder-to-protected aircraft distance is essentially the same for all these positions. The ellipsoid has the satellite at one focal point and the protected aircraft at the other; it is completely defined by specifying that its surface contains the position of the specific intruder being considered. The

thickness of the shell is proportional to twice the pulse width of the f_2 transmission. It should be noted that the system altitude limits and the duration of the receiving gate do not in any way reduce the volume that produces overlapping returns since the signals are combined at the antenna prior to signal processing.

However, if it were feasible to encode altitude data in terms of transmission frequency, then, by linear filtering, the elliposidal shell of ambiguity could be truncated by the horizontal planes defining the altitude region of interest. Unfortunately, it is not clear how this approach could be implemented within practical spectrum allocations. Because the ambiguity and transmission blind zones are a function of pulse duration, transmissions longer than approximately 1 to 10 μs are not feasible. Since these signals require about 0.1 to 1 megahertz of bandwidth, and since altitude data is needed from approximately 0 to 100,000 feet in increments of 100 feet, it would be necessary to have a spectrum allocation on the order of 10^2 to 10^3 MHz which is too wide to be feasible.

The airspace contained in the ellipsoidal shell associated with each intruder position is primarily a function of the closing airspeed. With high speed aircraft, the volume from which overlapped returns will be generated becomes large.

Consider, for example, two aircraft on a head-on level collision course where each has an air speed of (10^3) km/hr. Assume further that the $(T/\dot{T})$ threshold criterion is adjusted to provide 25 seconds warning and that the satellite elevation angle, ϵ , equals 60 degrees. Then the range separation, at the point of alarm indication, is 13.9 km. The co-altitude area, in the plane of the protected aircraft, from which other aircraft will generate overlapping signals, is given by

$$\text{Area} = \frac{4\pi C^2 \Delta\ (T+\Delta)}{(\sin\epsilon)^3} \tag{8}$$

where

T is the delay in the signal from the intruder and

Δ is the duration of each aircraft transmission.

For this case (head-on)

$$T = \left\{1 + \cos\epsilon\right\} \frac{R}{C}\ , \tag{9}$$

where R is the range at alarm indication. Hence, using the defined values of R and ϵ, T = 86.5 μs and

$$\begin{pmatrix}\text{Area from which overlapped}\\ \text{signals are received per}\\ \mu\text{sec of transmission time}\end{pmatrix} \approx 152\ (\text{km})^2 \tag{10}$$

Since aircraft usually fly in an altitude region of only about 10 km, the air space volume from which overlap is encountered can be approximated by a cylindrical shell. Hence,

$$\begin{pmatrix}\text{Volume from which overlapped}\\ \text{signals are received per } \mu\text{sec}\\ \text{of transmission time}\end{pmatrix} \approx 1520\ (\text{km})^3 \tag{11}$$

This volume, when combined with realistic aircraft densities and high closing rates, results in quite significant signal overlap problems. For example, in the vicinity of large airports, such as Chicago - O'Hare International Airport, as many as 600 aircraft can be aloft within 40 miles of the

airport. Assuming for simplicity that they are uniformly distributed within the volume, each aircraft occupies about 1520 $(km)^3$. Thus, with these parameter values and 1 μsec transmissions, approximately 7 aircraft would normally be contained in the volume from which signal overlap is experienced.

3.2.1.2 Multipath

The main signal transmitted from an intruder will ordinarily reach the protected aircraft on a direct line-of-sight path. Additional components of the signal will also be received via forward scattered paths and will be delayed with respect to the direct signal and usually reduced in amplitude.

However, the forward scattered signals will occasionally be of sufficient amplitude and delay to interfere with the direct signals. In addition, forward scattered signals from one intruder can overlap the direct signal of another intruder.

The incidence of this effect is frequent enough, particularly in terminal areas, to warrant further consideration with respect to SAVAS performance and signal processing.

3.2.1.3 "Second-Time-Around" Signals

A number of factors can cause considerable variation in the energy level of the f_2 transmissions. These include angular variations in omnidirectional antenna gain, changes in propagation loss due to weather, variations due to equipment aging, and so forth. Because of these, and because extremely low false alarm performance is needed to maintain user confidence and avoid unnecessary, possibly hazardous maneuvers, it is necessary to provide additional transmission power over that required to reach the outermost edge of the alert region under ideal conditions. Unfortunately the excess

power will then occasionally cause "second time" signals, which can overlap other intruder signals, unless the basic repetition rate is selected to minimize this problem.

3.2.1.4 Anomalous Propagation

Overlapping signals can also be caused by anomalous propagation (ducting, etc.) which results in the reception of substantial signals from distant aircraft, often beyond the line-of-sight.

3.2.2 Effects of Signal Overlap

Overlapping signals from individual aircraft will not be coherent and therefore the desired signal can be changed in any manner; further, the signals may be overlapped only over portions of their duration. Thus, signal interference will affect measurement of intruder altitude, time-to-proximity, and minimum slant range.

3.2.2.1 Altitude Measurements

Signal overlapping which garbles intruder altitude messages is the most serious effect encountered. In this situation, a co-altitude intruder on a threatening course could be judged as making a safe approach due to faulty altitude data. To minimize the problem, it appears desirable to transmit the entire altitude message, rather than a single bit, each period so that maximum redundancy can be attained. Since it is important to keep the transmission time to a minimum, this approach would require an increase in signal bandwidth by a multiple of almost 10 compared to transmission of a single bit per period.

In Section 4, techniques are described for rejecting garbled messages.

3.2.2.2 Time-to-Proximity Measurements ($T/\dot{T}$)

If $\dot{T}$ is determined by counting the number of returns received per fractional delay change, overlapping can cause pulses to be missed and can produce a higher value of $\dot{T}$ than actually exists. This, in turn, would tend to cause $T/\dot{T}$ to be in error and to generate false alarms.

3.2.2.3 Minimum Range Measurements

The danger arising from overlapped minimum range measurements is again from situations where the signals combine out of phase and returns are lost. Because the minimum range data is utilized primarily in situations where rates of closure are low, and hence the geometry may be changing rather slowly, the overlapping condition may persist for a substantial duration relative to the period available for evasive reaction.

3.2.3 Duplexing Situations Resulting in Loss of Signals

During the time that a protected aircraft is transmitting, messages from intruder aircraft on the same carrier frequency cannot be received. This results in an elliposidal volume about the protected aircraft in which the detection of intruders will be impaired. The ellipsoid has the satellite at one focal point and the protected aircraft at the other.

The intersection of this ellipsoid with the co-altitude plane of the protected aircraft is given by

$$R = \frac{C\Delta}{1 - \cos \epsilon \cos (a - \alpha)} \tag{12}$$

Thus, signals from co-altitude intruder aircraft in the region,

$$R \leq \frac{C\Delta}{1 - \cos \; \cos (a - \alpha)} \tag{13}$$

will be obscured by protected aircraft's own transmissions.

Two points should be emphasized: (1) the volume containing intruder positions from which messages to the protected aircraft are obscured by the protected aircraft's own transmissions, is not limited by a spherical volume of radius $C\Delta$; it consists of the entire ellipsoid defined above, and (2) assuming intruder transmissions of the same duration as the protected aircraft's, all intruder transmissions from within the ellipsoid will extend beyond the pulse width of the protected aircraft by some extent. In cases where these received pulses extend beyond the recovery time of the receiver, and also have sufficient amplitude to make up for the reduced signal energy and the losses due to mismatch between the effective pulse width and the receiver bandwidth, detection may occur.

3.2.4 Effects of Duplexing

The transmissions of the protected aircraft produce an ellipsoidal blind region surrounding the aircraft. Although some promising methods, discussed below, may reduce the extent of the blind region, transfer of altitude data appears very difficult to accomplish.

In view of these effects, it is necessary that the alert and alarm regions be appropriately scaled up so that all warnings are accomplished prior to aircraft entering the blind region.

Unfortunately, the blind region occupies a sizeable volume for reasonable transmission durations. In the most favorable satellite position, directly overhead, and with 1 μsec transmissions, the region extends approximately 500 feet down, and in the horizontal plane containing the protected aircraft, it extends 1000 feet.

When the satellite is not overhead, the maximum co-altitude distance from the protected aircraft to the ellipsoid is given by,

$$R = \frac{C\Delta}{1 - \cos \epsilon} . \tag{14}$$

At a 60 degree elevation, the maximum co-altitude extent of the blind region becomes 2000 feet, and for a 30 degree satellite elevation, this becomes about 7500 feet.

3.2.5 Possible Approaches for Reducing Duplexing Effects

One method for reducing the volume obscured by one's own transmissions would be to utilize an additional mode of operation in which periodic signals from the satellite would cause each aircraft to reduce its transmitter pulse width and increase its receiver bandwidth to match. Since only the close-in intruders would be of concern in this situation, the reduction in range performance should not cause difficulty. More significant possibly would be the equipment costs for the extra mode.

The simpler method of skipping f_2 transmissions periodically and listening for close-in intruders, encounters the problem of synchronization to prevent listening periods from coinciding. The possiblity of randomizing listening periods might be considered, and an analysis made of the performance statistics.

3.2.6 Situations Resulting in Spurious Signal Reception

This category includes situations generated by the phenomenon discussed in Section 3.2.1, which do not involve signal overlap. Thus, situations involving non-overlapping spurious signals arising from multipath,

second-time-around signals, and anomalous propagation would come under this heading. In addition, signals due to EMI are also included in this category.

3.2.7 Effects of Spurious Signals

The specific effects of spurious signal reception are quite dependent upon the specific signal processing techniques utilized. If multiple tracking channels are employed, interference effects should be minimized. The situation then becomes quite similar to conventional radar tracking in the presence of noise and EMI, a problem which has been extensively studied and reported in the literature.

Considerably different effects would be encountered using the technique mentioned in Reference [1], which consists of determining $\dot{T}$ by counting the number of pulses received in a fractional gate. In this case, extra pulses produce an erroneous reduction in the magnitude of $\dot{T}$, and as a result, $T/\dot{T}$ is increased. This type of error could be extremely serious since it could effectively reduce the warning time below the period required for evasive maneuvers.

SECTION 4

SAVAS EQUIPMENT CONSIDERATIONS (TWO-FREQUENCY SYSTEM)

In order to properly evaluate the equipment feasibility in the SAVAS system, it would be necessary to establish a specific set of SAVAS system requirements along with allowable measurement tolerances. For instance, it is necessary to know minimum and maximum ranges, minimum and maximum closing velocity, required resolution between multiple intruders, and the number of intruders which must be evaluated as a collision threat in a given time interval. Since satellites are involved in the SAVAS system, it is necessary to know their orbital parameters in order to determine maximum ranges (dynamic range) and doppler frequency.

Furthermore, pilot reaction time, flight dynamics, and flight doctrine all affect the kind and amount of equipment that is required, what display the pilot should have, and how soon the information must be displayed in order to take evasive action.

In short, at this point in the study a number of plausible assumptions must be made before any equipment evaluation is possible. It is important, therefore, in the following discussions that equipment configurations should not be construed to be optimum with respect to a specific set of operational requirements. The discussions are meant only to isolate general problems and to estimate the amount and complexity of equipment required to perform the proposed SAVAS measurements. Whether or not such measurements provide a sure method of collision avoidance is not addressed here.

From the equipment point of view, only the multi-intruder case will be discussed.

It is important to note what measurements are made in the SAVAS system. Figure 10 contains an exaggerated view of the system geometry. This geometry is a dynamic geometry and not a static one. The satellite moves in its orbit and the aircraft at A and B have a velocity relative to each other and to the satellite. All distances are continually changing. Each aircraft must track the satellite pulse in time (a factor if multiple pulse integration is to be used). In particular, for the geometry shown in Figure 10, the time difference between the f_2 transmissions of aircrafts A and B decreases at a rate determined not only by the relative closing velocity of the aircraft but also by the velocity of the satellite (weighted by a function of its position). While the distance S-D in Figure 9 may be small for closely spaced aircraft, the rate of change of S-D may be large enough to mask the relative closing velocity of the aircraft during the fractional gate measurement interval. In particular, if $\dot{R}$ is zero, the fractional gate will measure the rate of change of S-D. The magnitude of the error due to the above discussion has been discussed in Appendix III, and no further note will be made of it here. Equipment considerations will be assumed to measure T and $\dot{T}$ as shown in Figure 10.

4.1 SATELLITE ORBIT ASSUMPTIONS

Time limitations in this study did not permit extensive investigation of satellite orbits which would give the required coverage for the SAVAS system. It is assumed that a number of satellites placed in approximately synchronous, highly elliptical orbits would be established so that at least one satellite would be in view of a coverage area at a given time. In the SAVAS system, it is mandatory that all aircraft be synchronized by the same satellite within a given coverage area. Furthermore, the elevation angle of the satellite from all aircraft in the coverage area should be sixty-degrees or greater;

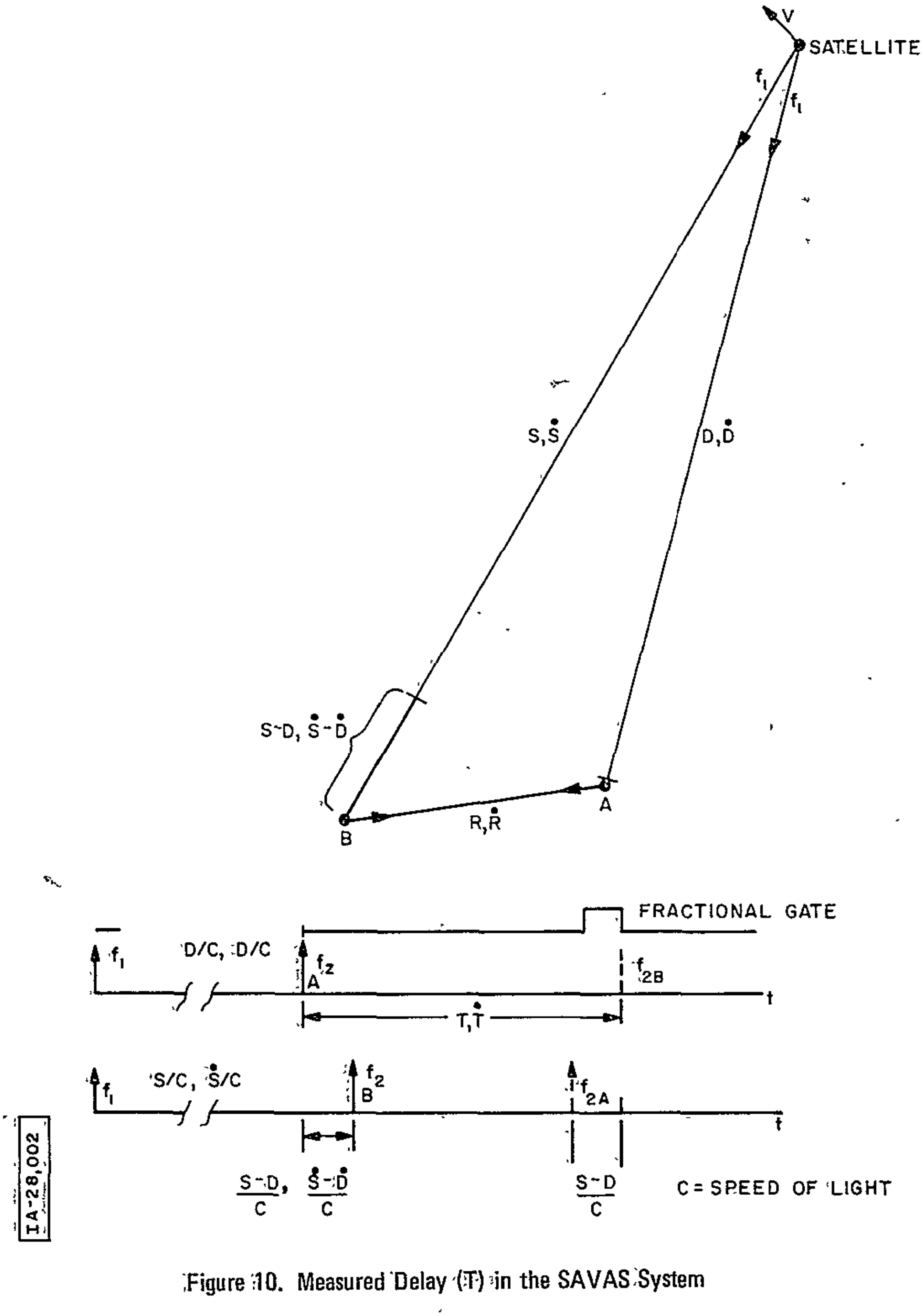

Figure 10. Measured Delay (T) in the SAVAS System

otherwise alarm and alert regions become too distorted (See Figures 3 to 7). The problem of synchronizing all aircraft to the correct satellite has not been solved, but presumably satellite pulse or frequency coding along with operational directives could be used for this purpose. The practicality of this technique requires more study.

For purposes of power calculations and to determine general satellite-to-earth communication problems, the orbital configuration shown in Figure 11 has been assumed for this study. A satellite apogee of 40,000 km has been assumed (typical of synchronous orbits). Antenna pattern coverage of the earth's diameter plus 100,000 feet of atmosphere has been assumed. The required satellite antenna beam-width is about 17.2 degrees. Elementary calculations show that the antenna power gain would be about 20-db (assuming an efficiency of 70 percent).

It would be necessary to provide dynamic beam orientation to keep the main lobe pointed at the earth as the satellite progresses around its orbit. This problem, along with the method of generating primary power, satellite life, etc., are relevent questions but are beyond the scope of this report.

The size and weight of an antenna to form a beam suitable for earth illumination such as depicted in Figure 11 should be well within the state of the art at UHF (L-Band). In particular, lightweight antennas built of metalized fiber glass and foam construction have been space qualified [2].

General considerations of the distortion of the alarm region as a function of satellite elevation angle show that the satellite would only be usable at elevation angles greater than sixty degrees. Therefore, the satellite would have to be relatively high in its elliptical orbit, maximum and minimum ranges would be relatively great, and useful coverage area would be limited when this constraint is taken into account.

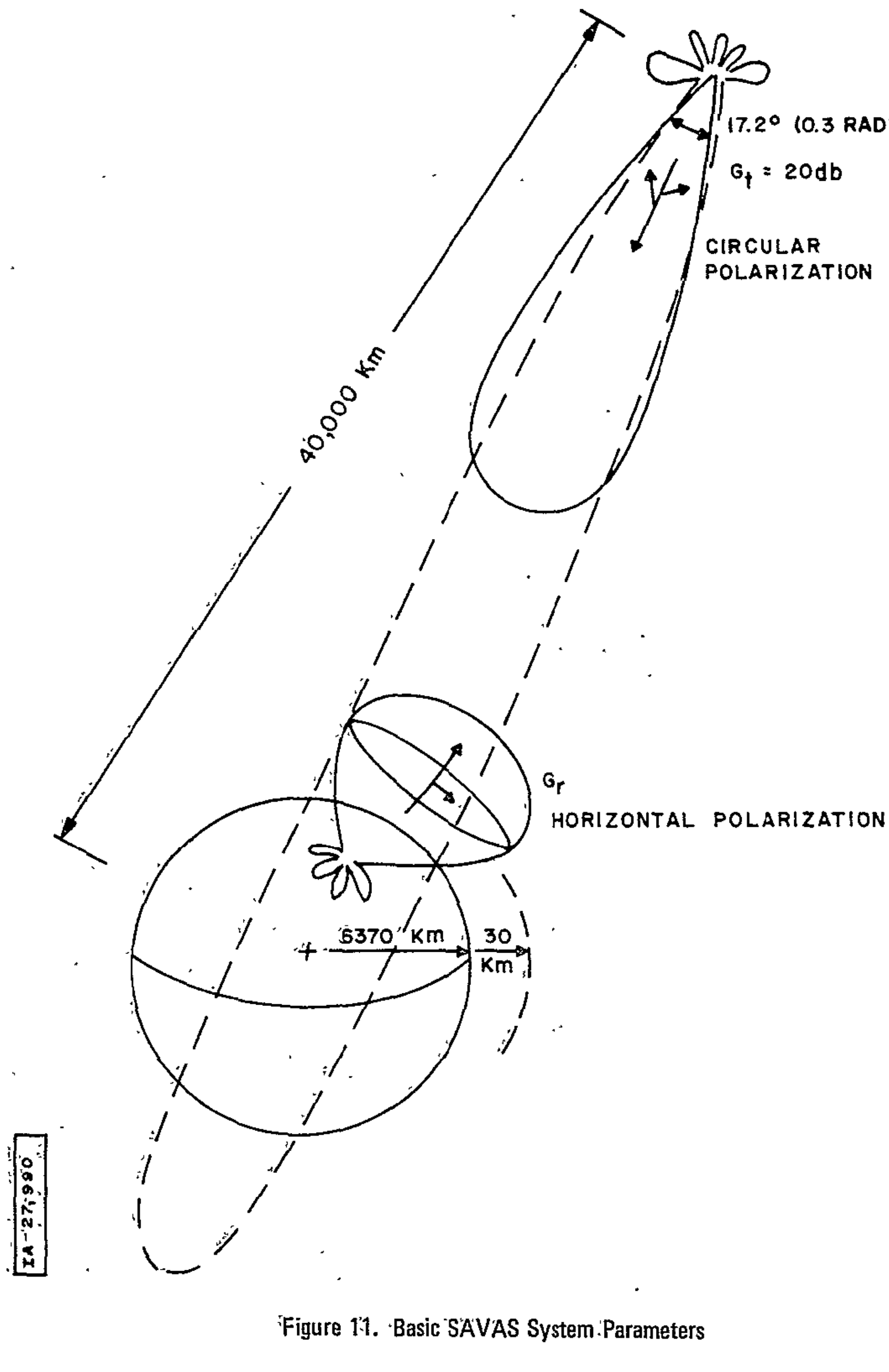

Figure 11. Basic SAVAS System Parameters

4.2 GENERAL DISCUSSION OF SATELLITE-TO-AIRCRAFT PATH

The general communication path between a SAVAS satellite and an aircraft is shown in Figures 11 and 12. Because the aircraft antenna axis can have almost any orientation with respect to the satellite beam axis, especially if the aircraft is maneuvering, the satellite emission should be circularly polarized. Since the useful elevation angle is about sixty degrees, the aircraft requires an antenna pattern coverage of about ninety degrees about its vertical axis. Horizontal polarization of the aircraft pattern would make reception relatively independent of angle to the satellite. There would be a 3-db coupling loss between the horizontal and circularly-polarized antennas.

Flush mounted, cavity-backed spiral antennas can be used to provide the depicted aircraft antenna characteristics. Coverage almost to the horizon is possible with these antennas. Double-arm or four-arm spirals used in conjunction with beam-forming networks can be used to measure the direction of incident energy from the satellite. The diameter of a spiral is approximately one wavelength.

The output of any antenna is a function of the total field to which the antenna responds and not just the field in its main lobe. Therefore, in general, the output is a function of components of beam orientation loss as well as aperture-to-medium coupling loss that may result from scattering by the troposphere, by multipath due to rough or irregular terrain, and by terrain clutter such as vegetation, buildings, bridges, or power lines. The effects of tropospheric scatter at L-band are small. Figure 12 shows a simplified version of the effects of multipath due to local terrain. It is possible that antenna misorientation coupling through side lobes can almost equal coupling through the main lobe.

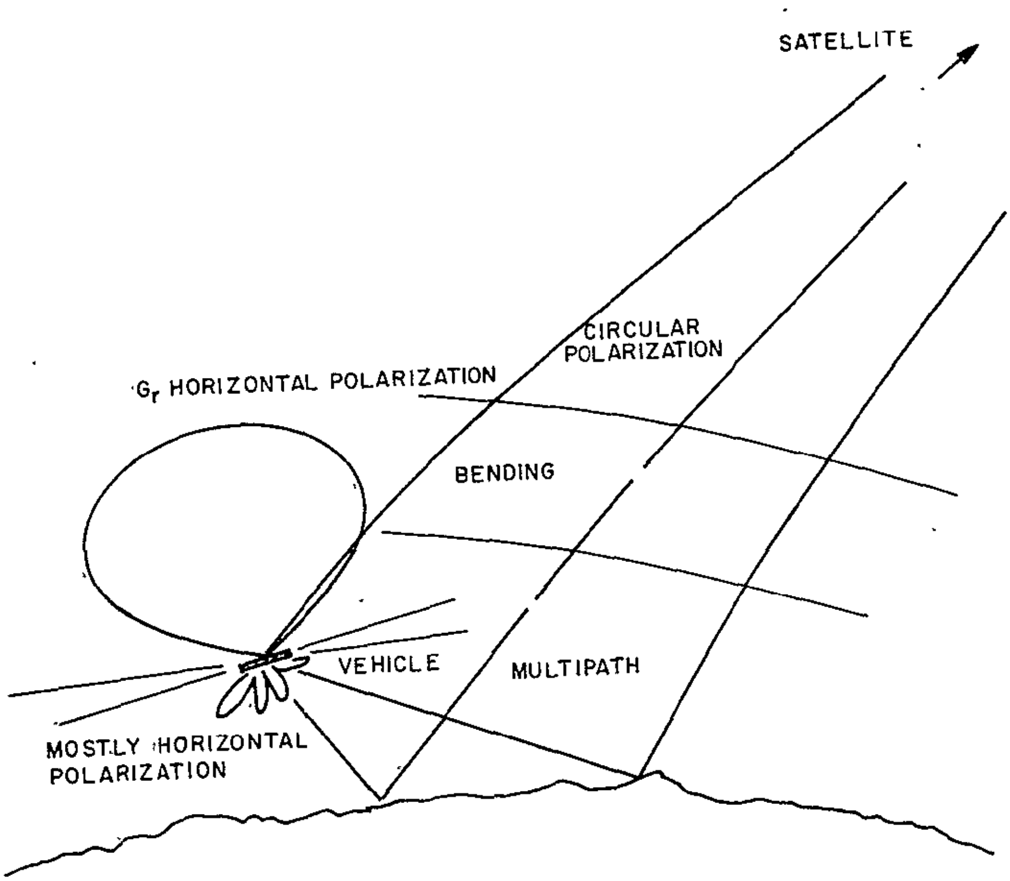

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Figure 12. Satellite to Aircraft Multipath

The total effect of multipath is to produce a lobe structure in space where the depth of the nulls are filled in by diffuse scattering and tropospheric phase diffusion. Typical lobing structure can vary 20-db or more[3]. Since lobe structure is a function of wavelength, it is very unlikely that aircraft in the same general vicinity will experience identical multipath conditions.

Multipath also interferes with synchronization performance because of the signal fading that results from the lobing structure.

This problem can be alleviated by proper AGC in the system receivers and by controlling antenna side lobe response which is difficult to do on aircraft. If the satellite timing signal is narrow-band, for instance, a low frequency sine wave modulating a carrier, the effect of multipath will be to shift the phase of the sine wave envelope and thus produce synchronization timing errors. A relatively small phase shift in a low frequency wave produces relatively large microsecond timing errors. This problem can be alleviated by tracking the satellite with a very narrow beam having very low side lobes – probably an impractical solution.

One remaining solution to the synchronization problem is to transmit relatively narrow pulses from the satellite so that direct path and multipath reception can be resolved in time and amplitude. The receiver gain could then be controlled by a gated AGC on the highest amplitude signal. But even this solution is not without problems. If the multipath signal is resolved from the direct path signal, there is a danger of locking on to the multipath signal unless provision is made to prevent this. If the multipath signal overlaps the direct signal, pulse broadening will occur with constructive or destructive interference; this would affect the symmetry of the composite pulse, and therefore, the timing accuracy.

For the remainder of the discussion on equipment configuration, it will be assumed that the form of synchronization from the satellite will be in the form of a pulse with a repetition rate to be determined later.

4.3 SATELLITE-TO-AIRCRAFT TRANSMISSION CALCULATIONS

The basic calculation formulas in References [3] and [4] for one-way transmission between a transmitting site and a receiver site were used for power calculations. If the basic transmission loss (that is, not including directive gain) in free space is denoted as:

$$L_{fs} = 20 \text{ Log} \left(\frac{4 \pi R}{\lambda} \right) = 32.45 \text{ db} + 20 \text{ Log } f + 20 \text{ Log } R \tag{15}$$

where R is in kilometers and f is in megacycles, it is seen that when low gain antennas are used, the frequency dependence in Equation (15) indicates that the service range for UHF can be made equal to that in the VHF band only by using additional power in direct proportion to the square of the frequency. However, for a given antenna size more gain can be obtained at UHF than at VHF, thus partially compensating for this effect. Space loss as a function of frequency is plotted in Figure 13 for antenna separation of 40,000 kilometers. The frequency selection trade-off is between transmitter power and antenna size for the required directive gain on both the satellite and the aircraft.

A frequency of 1200 MHz was selected for power budget calculations used in this study. This frequency falls in one of the bands reserved for navigation (960 to 1215 MHz) and is close to optimum for satellite-to-earth transmission, when antenna effective noise temperature is accounted for.

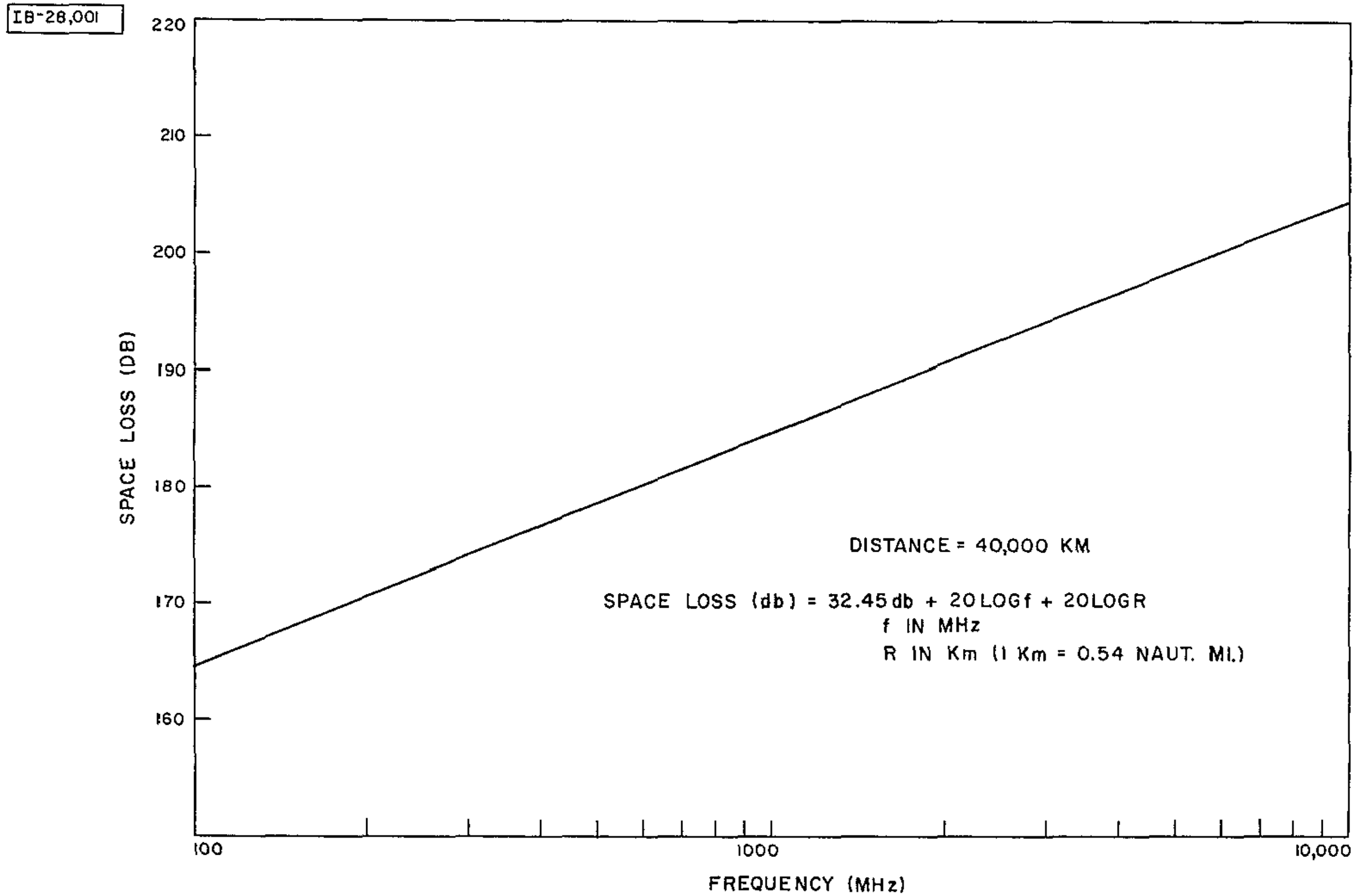

Figure 13. Space Loss As A Function of Frequency

A summary of the satellite-to-earth power calculation is given in Table II. The calculation is based on the power required to produce a single pulse, 17.5 db signal-to-noise (S/N) ratio at the output of a matched filter. This signal to noise ratio produces a 0.99 probability of detection with a 10^{-6} false alarm rate. It is seen that approximately 40 kilowatts of peak power is required in the satellite. This amount of peak power for a long life satellite is not within the present state of the art. However, by using a suitably coded pulse whose autocorrelation function is an impulse (for example, a 13-bit Barker code),[5] the peak power can be reduced by a factor of thirteen, which is within the state of the art. The matched filter for a Barker code is a suitably-tapped delay line followed by an integrator. This technique complicates the transmitter modulator and the receiver demodulator, but not unduly so.

Up to this point, the discussion has centered around a single pulse signal-to-noise ratio from a matched filter. Pulse processing can be used to enhance the average timing accuracy and to reduce the variance of the average. Furthermore, the false alarm rate can be reduced to negligible proportions by gated pulse tracking. Figure 14 contains a simplified block diagram of one method of pulse tracking and smoothing. Since the maximum signal-to-noise ratio of a matched filter output is at the peak of the pulse, the pulse is first split using a delay line and a comparator. Pulse splitting by a factor of five is easily realized by this method. The output from the comparator is fed to a voltage-controlled multivibrator servo loop whose overall transfer function is a low pass filter to variations in the time difference between the output pulse and the noisy input pulse. Setting the loop time constant determines the number of integrated pulses. Other closed loop responses can be realized by changing the open loop transfer function.

Table II

Power Calculations

$$S_r = P_t + G_t + G_r - L_t - F_p - L_R - \text{Space Loss} \pm \text{other db (watts)}$$

Satellite Antenna Gain (17.2° Beam Width; $\eta = 0.7$)	20 db
Satellite Cable Losses	1.5 db
Space Loss (1200 MHz; 40,000 km)	185.5 db
Polarization and other losses	3.0 db
Tropo propagation Loss	3.0 db
Aircraft Antenna Gain	0 db
Aircraft Cable Loss	1 db
Net Loss	175 db
Effective System Temperature	714° K
System Noise Power Density (N_o)	-200 dbw/Hz
Matched Filter $2E/N_o$ for 0.99 Probability of Detection and 10^{-6} false alarm rate.	+17.5 db
Pulse Width: 2 μ sec. PRF = 250 PPS	
Required Receiver Peak Signal Power	128.5 dbw
Peak Transmitter Power Required (40 Kw)	46.5 dbw
Average Transmitter Power (20) watts	

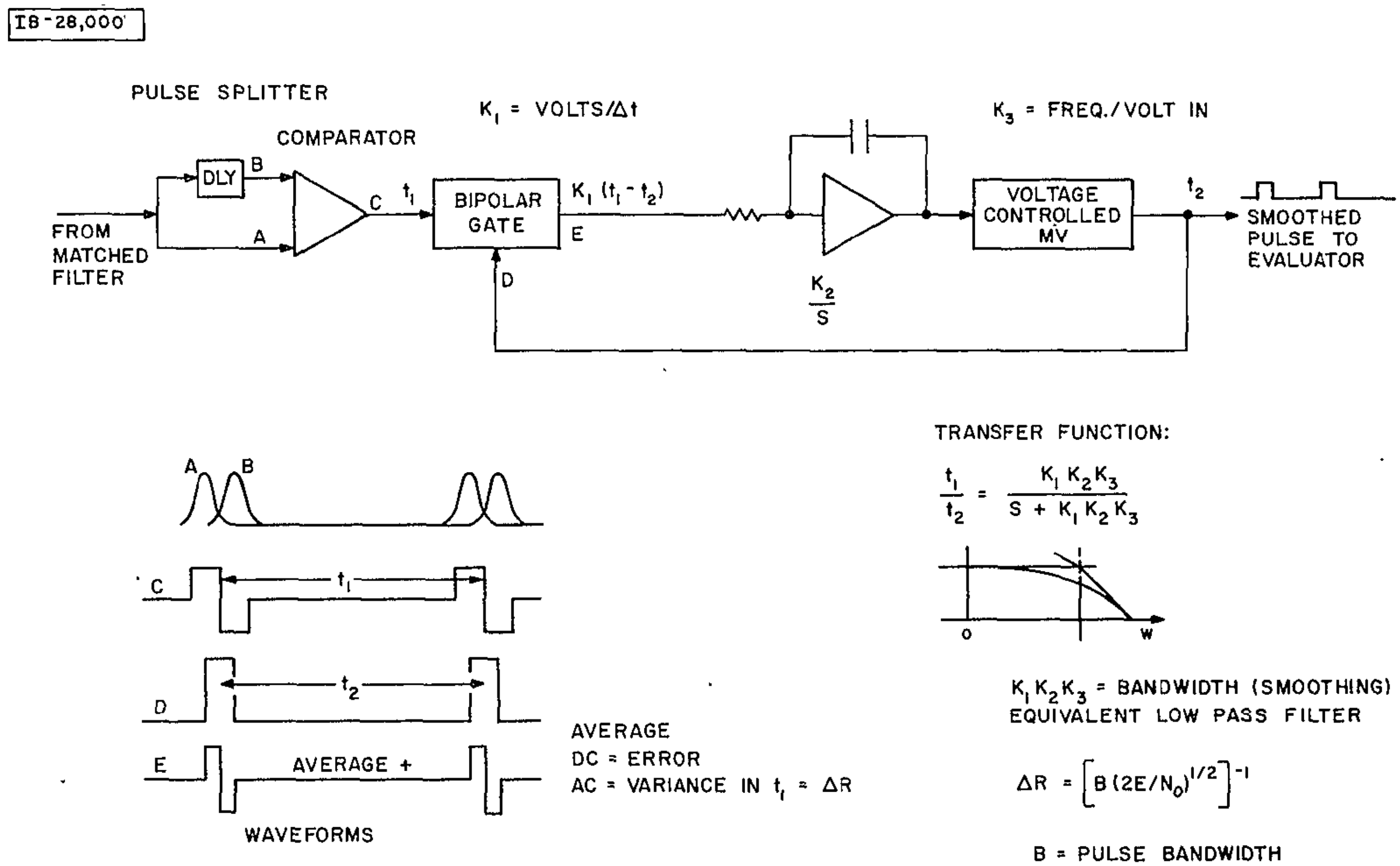

Figure 14. Pulse Tracking and Smoothing

Some care must be used in selecting the closed loop integrating response. With respect to a given reference time, the satellite synchronization pulses received at the aircraft move in phase due to the changing distance between the aircraft and the satellite. Integration is basically a lag function; therefore excessive lags in the aircraft synchronization may result if the integration time is too long and not well matched between aircraft.

The variance in measuring the time of arrival of a pulse output from a matched filter is given by:

$$\Delta R = \frac{1}{B\left(\frac{2E}{N_o}\right)^{1/2}} \times \frac{1}{\sqrt{N}} \times \frac{1}{\eta} \quad , \tag{16}$$

where ΔR is the variation in measurement due to noise, N is the number of pulses integrated, and η is the integration efficiency. For example, if ΔR is required to be $0.1\ \mu$ sec, N to be 10, and $\eta = 0.8$ (typical for a low pass filter), then for a 17.5 db signal-to-noise ratio the required pulse bandwidth is about 525 KHz. The pulse width corresponding to this bandwidth is about 2 μsec. Splitting this pulse by a factor of 5 would allow a timing accuracy of $\pm\ 0.3\ \mu$ sec (neglecting equipment group delay shift due to doppler and variations in tracking filter lag from aircraft to aircraft). The uncertainty in the protection zones for this case would be $\pm$ 90 meters, plus variations in equipment delay from aircraft to aircraft.

Other trade-offs between satellite power, signal-to-noise ratios, smoothing constants, and accuracy are possible. The above discussion is an example only. Furthermore, the pulse tracking and smoothing function can be performed using operational digital techniques. The analog configuration shown in Figure 14 was chosen for its simplicity. It can be built from

readily available off-the-shelf integrated circuits. Some digital techniques will be treated later, where intruder evaluation is discussed.

4.4 AIRCRAFT-TO-AIRCRAFT TRANSMISSION CALCULATIONS

In the proposed SAVAS system, a signal from a satellite synchronizes pulse transmissions from all aircraft in a given area. Each aircraft receives a pulse transmission from every other aircraft. By measuring the time delay between the receipt of the satellite signal and other aircraft signals, a measure of proximity can be obtained. In particular, a gate can be established in a protected aircraft such that if a signal falls within the gate and furthermore is within a coaltitude corridor, an intruding alert can be sounded. The above operation presupposes that "own altitude" is included in the transmissions between aircraft.

Delay accuracy and delay resolution are the major considerations in aircraft-to-aircraft transmission. Equation (16) shows that delay accuracy and variation due to noise is a function of bandwidth only. That is, any pulse width can be used as long as it has a sharp leading edge. However in order to resolve closely spaced aircraft, it is necessary to use very narrow pulses. For want of system requirements, a 1 μ sec pulse has been selected for this study (corresponding to a 300 meter separation). The matched filter bandwidth is about 1 mHz. The matched filter is used because it gives the maximum peak signal-to-noise ratio in a system and is particularly adaptable to pulsed signals.

It should be pointed out that the use of pulse-width modulation for altitude encoding reduces the effectiveness of matched filtering because the optimum match exists for one pulse width only. Altitude encoding is discussed in Section 4.6 below.

A summary of aircraft to aircraft power calculations is shown in Table III. The calculations are based on a 17.5 db signal-to-noise output from a matched filter at a distance of 30 nautical miles. This signal-to-noise ratio gives a 0.99 probability of detection with a 10^{-6} false alarm rate. For a 1-MHz bandwidth, there would be about one false alarm per second; however by using gated tracking with smoothing, the false alarm rate can be reduced to negligible proportions.

The required peak transmitter power for the above performance was calculated to be about 10 watts at 1100 MHz. This does not include fading due to the lobing structure of multipath. Figure 15 shows the free space loss as a function of aircraft separation with frequency as a parameter. The required peak power is well within the state of the art using solid state devices.

The basic problem of communication between aircraft with omni-directional-like antenna patterns is multipath. Vertically-polarized antennas on the aircraft help prevent in this, but do not eliminate the problem. The reflection coefficient of rough terrain can be as high as 0.8 for horizontal polarization and 0.4 for vertical polarization. Over the sea, there is an order of magnitude of difference. The result of multipath for overlapping signals is a very deep lobing structure, or multiple signals for resolved reflections. It would be very difficult to separate direct paths from multipath on the basis of amplitude over a very large dynamic range. Figure 16 shows a simplified version of multipaths between two aircrafts. Similar paths exist between the third aircraft and the other two aircraft. In addition to the multipaths shown, there are relatively low attenuation paths due to ducting in tropospheric inversion layers and reflections from ionized cloud formations. In short, the SAVAS system appears to have all of the multipath problems that limit most other responding systems proposed for collision avoidance. An

Table III

Summary of Aircraft-to-Aircraft Power Calculation

$$S_r = P_t + G_A + G_B - L_t - F_p - L_R - \text{Space loss} \pm \text{other db (watts)}$$

Sum of Aircraft Ant. Gains	0 db
Trans. Multiplexer Loss	2 db
Other Losses	3 db
Receiver cable + MPLX Loss	2 db
Space Loss (1100 MHz; 30 Mi.)	127.5 db
Net Loss	134.5 db
Effective System Noise Temperature	815° K
System Noise Power Density (N_o)	-200 dbw/Hz
Matched Filter $2E/N_o$ for 0.99 Probability of detection and 10^{-6} false alarm rate Pulse width: .1 μ sec; PRF 250 PPS	+ 17.5 db
Required Peak Signal Power at the Receiver	-125.12 dbw
Peak Transmitter Power Required (8.67 w)	9.38 dbw
Average Transmitter Power (2.5 mw)	

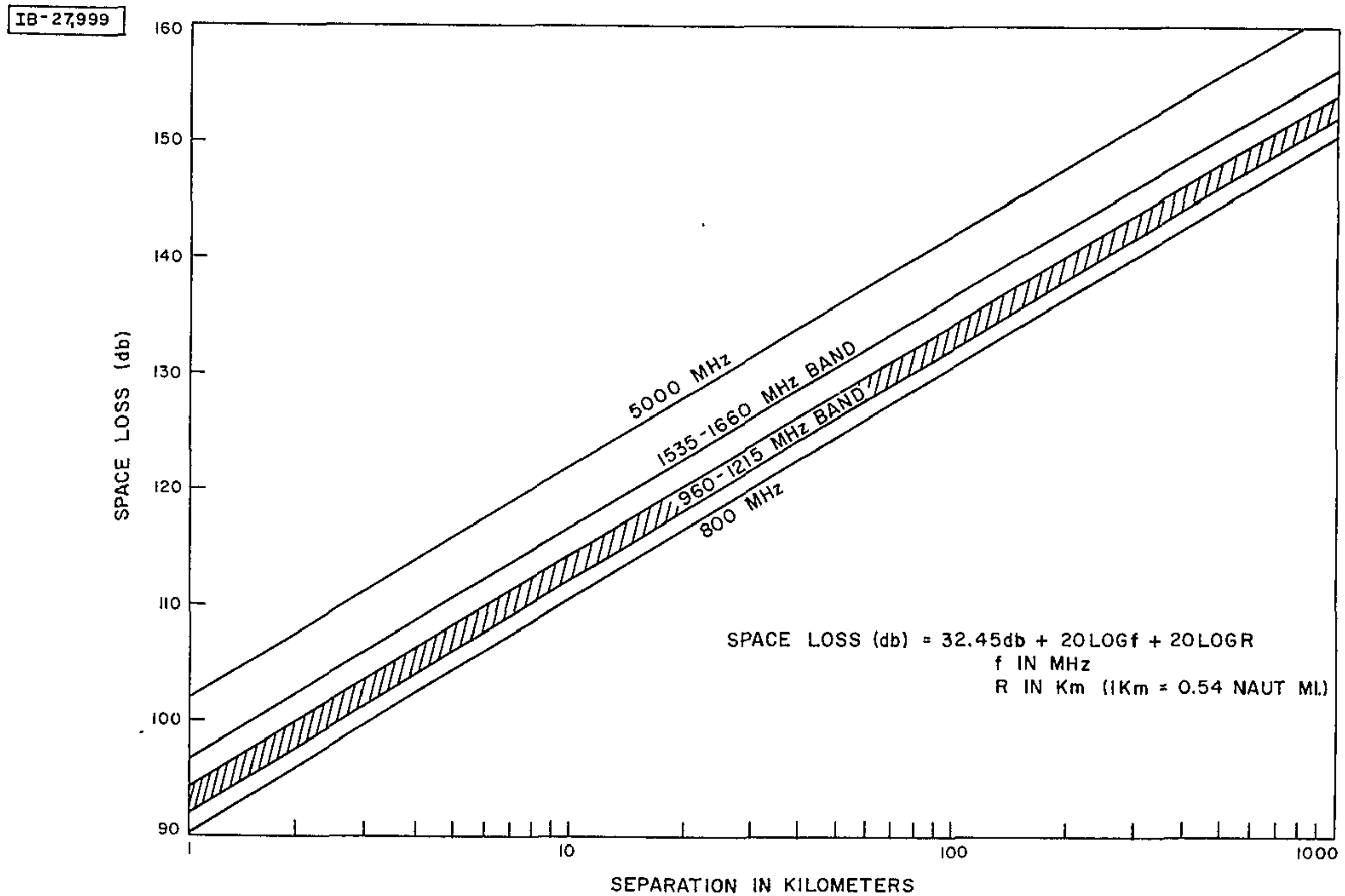

Figure 15. Aircraft to Aircraft Space Loss As A Function of Separation

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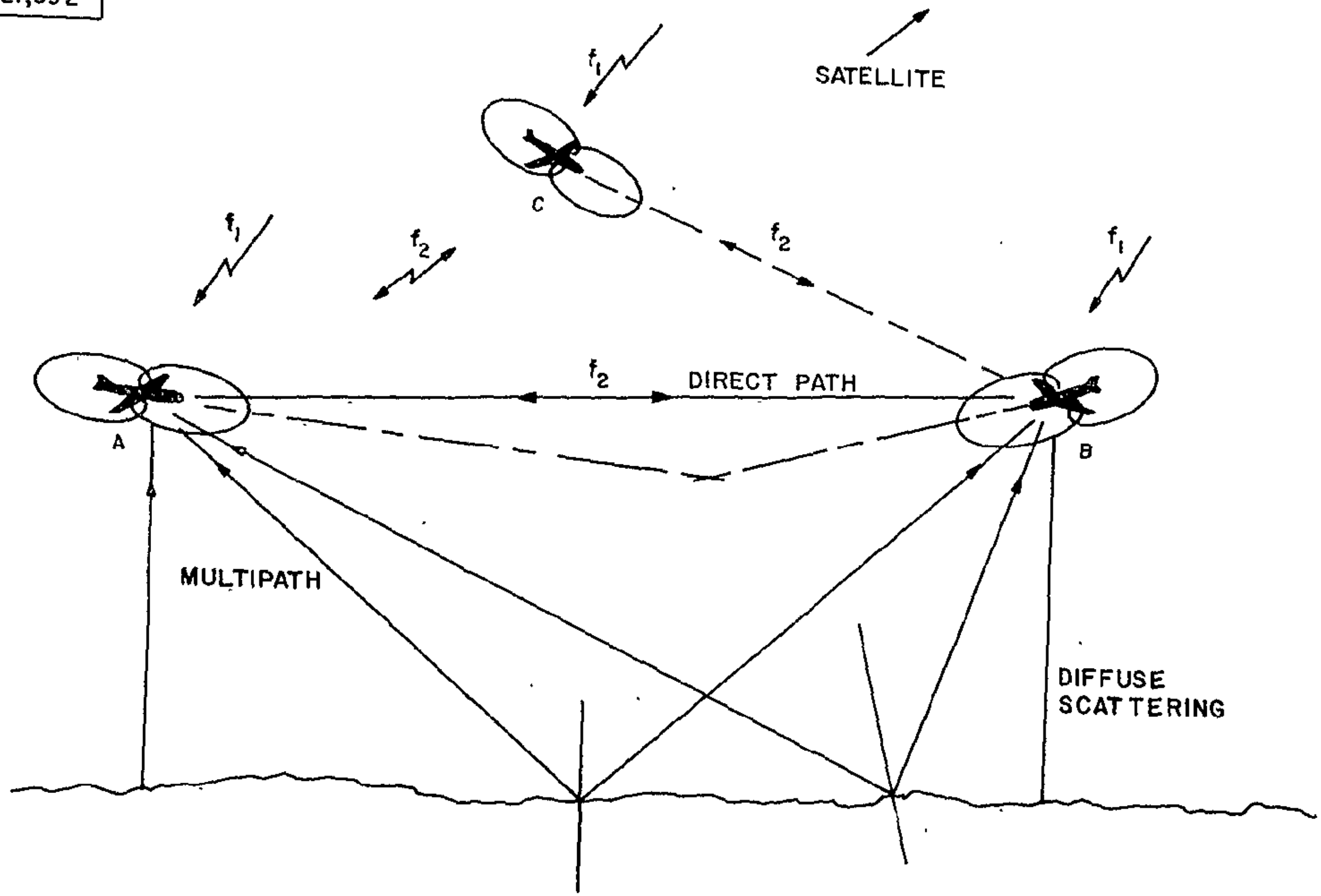


Figure 16. Aircraft to Aircraft Multipath Consideration

increase in transmitted power to compensate for fading and antenna lobe irregularities will only accentuate the general multipath problems.

In order to reduce the effects of scattering from the ground, the elevation coverage of the antennas should be restricted. The aircraft antenna coverage could consist of two vertically-polarized azimuthal cardioid patterns with limited coverage in elevation. Two antennas arrays, one forward and one aft, could provide such patterns. At 1100 MHz, the antenna array would require about two feet in the vertical plane for 20 degrees elevation coverage. The forward and aft azimuthal patterns could be made to overlap to provide side coverage. The patterns could be selected so that the sum of any two aircraft antenna gains is not less than zero db in the azimuthal plane. Elevation coverage could be selected as a trade-off between minimizing multipath problems while maintaining sufficient altitude corridor coverage. A secondary effect of limiting altitude coverage would be to accentuate processing only those intruders that are close to the protected aircraft's own altitude in level flight, or the altitude toward which the aircraft may be climbing or decending.

Double, and four-arm cavity-backed, flush mounted spiral antennas used in conjunction with beam-forming networks can be used to determine direction finding information. These antennas typically provide ninety-degree coverage patterns, and at least four antennas would be required – one in each quadrant. Rough direction finding in elevation and azimuth can be accomplished by using sum and difference patterns from a four-arm spiral. The operation is similar to monopulse technique. It is, of course, relatively expensive.

4.5 SATELLITE-TO-AIRCRAFT SYSTEM BLOCK DIAGRAM

It has been pointed out previously that a narrow-band timing signal from the satellite may be impractical because of multipath effects. Furthermore,

a narrow-band doppler tracking receiver would be required to maintain a reasonable S/N for the narrow band signal. Therefore a pulsed signal (possibly coded) is proposed.

Figure 17 shows a simplified block diagram of a satellite-to-aircraft pulse receiver for the f_1 pulse. Calculations in Section 4.3 suggest a 2 μ sec pulse width which, after due processing, would provide a $\pm$ 0.3 μ sec timing accuracy.

The overall bandwidth of the RF-IF section of the receiver would be 600 KHz allowing $\pm$ 50 KHz doppler shift. The problem in this portion of the receiver would be to control group delay as a function of signal amplitude and doppler shift. Differences in delay from aircraft to aircraft would add to protection zone uncertainty.

Additional pulse matching can be provided by a post-detection integrator time constant (1.8 μ sec for a 2 μ sec pulse). Using this scheme, a doppler tracking receiver would be unnecessary.

A threshold could be used to discriminate against low level multipath signals. Pulse tracking and smoothing (as described in Section 4.3) could be used to enhance timing accuracy and reduce variation due to noise and interference. Keyed AGC would maintain pulse shape which could vary excessively over the wide dynamic range of the input signal from the satellite. As a fail-safe measure, some indication would have to be made that a pulse is being received and that the pulse tracker had locked on to it. This can easily be implemented by pulse rate integration for pulses exceeding a threshold and by sensing the pulse tracking loop error.

Solid state gain is available in the 1200 MHz region, and there is no reason why the entire receiver could not be made extremely small and lightweight. If modern microelectronic techniques using thick and thin

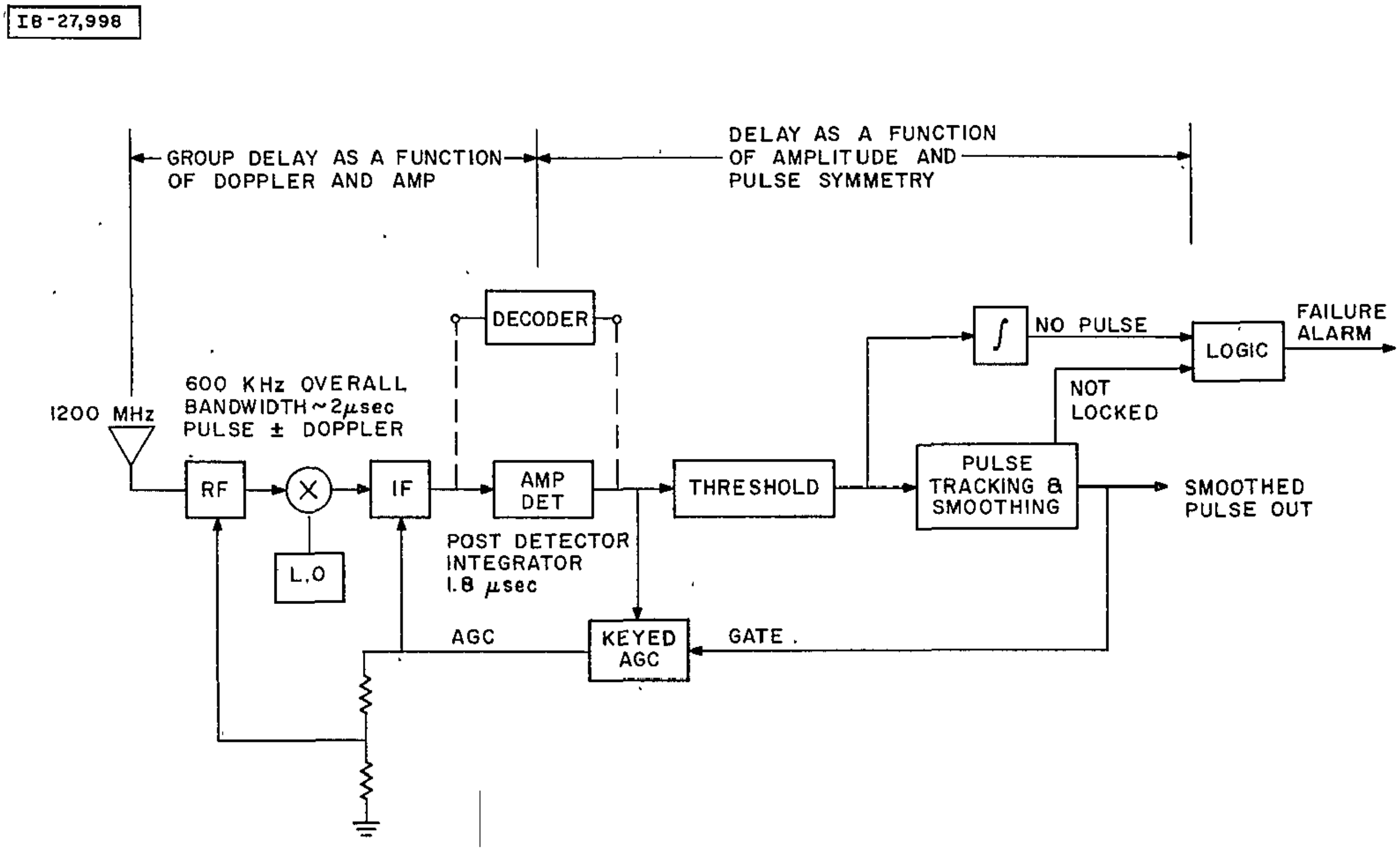


Figure 17. Simplified Block Diagram Aircraft Satellite Receiver

films were used, the receiver characteristic would be reproducable, and could be easily mass-produced for reasonable cost.

4.6 AIRCRAFT-TO-AIRCRAFT SYSTEM BLOCK DIAGRAM

In the proposed SAVAS system, a satellite timing signal is received at each aircraft in a coverage area. This signal is used to synchronize an RF-pulse transmission from each aircraft to every other aircraft in the coverage area. The transmission from a particular aircraft contains "own altitude" information which can be decoded at each receiving aircraft to determine the altitude difference between the sending and receiving aircraft. By measuring the time difference between reception of the satellite signal and other aircraft signals (designated as T in this report; see Figure 10), a measure of proximity can be derived. Furthermore, by evaluating T and $\dot{T}$, a measure of the "time-to-go" to a possible collision can be made.

The equipment required on a protected aircraft is a satellite antenna and receiver to provide the master synchronizing signal (these items have been discussed in Section 4.5), an aircraft transmitter which is capable of encoding digital information, a receiver which can decode digital information and provide intruder signals, and an evaluator which can process multi-intruder signals and provide threat information to the pilot in time to take effective evasive action.

The basic problems in evaluating aircraft-to-aircraft signal processing equipment are the multipath problem and signal overlap from multiple intruders. Multipath problems have been discussed in Section 4.4. At this point in the study, there is no obvious solutions to the multipath problem except those already mentioned. The multipath intruder signal overlap problem is discussed in Section 4.6.5.

Figure 18 shows a simplified block diagram of a plausible aircraft SAVAS system. The entire system is synchronized by the smooth output pulse from the satellite receiver shown in Figure 17. The system is based on sending and receiving a 1 μ sec pulse between aircraft.

4.6.1. Antenna Switches and Diplexer

The forward and aft antenna switches, as well as the send-receive RF-multiplexing switch, can be implemented with modern PIN-diode solid state switches. These switches have typical isolations of 50 db at 1100 MHz and typical switch settling times of less than 0.1 μ sec. Several hundred watts of peak power can be handled. Therefore, the receiver recovery time between transmit and receive would be determined primarily by the receiver bandwidth. Gating the receiver chain would prevent processing leakage signals. However, if one channel were assigned to process the leakage signal, a closed loop self-check could be made in the system.

4.6.2 Aircraft Transmitter and Modulator

Solid state gain at 1100 MHz and a peak power level of 20 watts is within the state of the art.

Assuming that digital data is coded on the f_2 pulse by sending one bit per period, the modulator could consist of a pulsed frequency shift keyer. The frequency would depend on whether a primary one or a zero is to be transmitted. For a 1 μ sec pulse, the required shift would have to be about 1 MHz; otherwise the pulse spectra would overlap. This would require an overall bandwidth of about 2 MHz in the transmitter receiver chain. Matched predetection filters could be used at the receiver bi-polar detector input to separate binary ones from zeroes.

There may be more optimum forms of bi-polar modulation for sending digital data, but time did not permit detailed study of this matter. In any event, group delay through the system must be matched from aircraft-to-aircraft to prevent excessive error in alarm region boundaries.

4.6.3 Aircraft Digital Data Encoder

The bandwidth requirements to send all of the digital data during a single repetition pulse might be impractical in this system. However, the digital data can be sent serially: one binary bit for each repetition pulse. Since the pulse is also to be processed as intruder position, each pulse must be coded as a binary one or a binary zero, and it must be synchronized with the satellite f_1 pulse. Furthermore, in order to process serial binary data, it is necessary to be able to derive data (one or zero), timing (bit position), and sync (end of binary word) at the receiver.

There are many methods of sending serial digital data and deriving the required information to process it. The equipment is categorized as digital data modems (modulator – demodulator). The digital data link depicted in Figure 18 shifts four bits at a time into the coder where it is changed to a five-bit redundant code with at least one bit in each code group. A special code is used to develop the message sync pulse in the receiver. The redundancy in the code group is used to develop timing information in the receiver. The five-bit group is shifted into the transmitter modulator one bit at a time in synchronization with the satellite synchronization pulse. The control box developes the 4 for 5 bit shift signals and other system timing pulses. The digital data link technique described above is well known and has been used on radio links and land-lines.

Other data link configurations are possible, but the special requirements of the SAVAS aircraft signals must be kept in mind; that is the signals

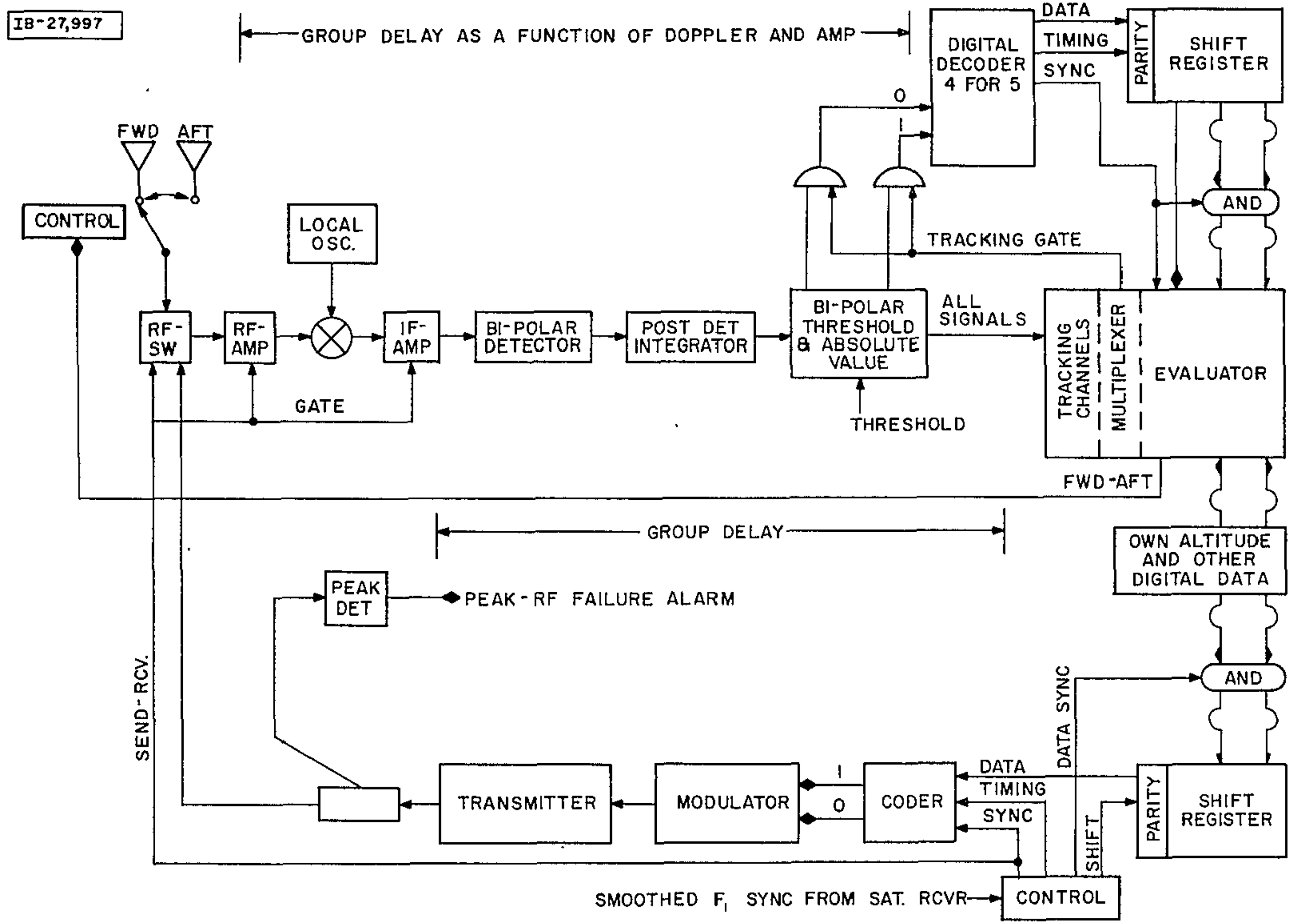


Figure 18. Aircraft System Block Diagram

not only transmit binary data, they also must be accurately timed in order to determine aircraft separation. It is doubtful whether links with these special requirements are presently commercially available, but their development should be well within the state of the art.

4.6.4 Receiver

The RF, IF, and local oscillator portions of the aircraft-to-aircraft receiver are well within the present state of the art using modern micro-miniature techniques. Figure 15 shows that the receiver would have to operate over about a 40 db dynamic range; AGC probably could not be used. The receiver would require very fast recovery for overload signals in order to resolve closely-spaced intruder signals. It would also require well-controlled characteristics for overlapping signals. Group delay as a function of frequency and signal amplitude would have to be well-matched from aircraft to aircraft in order to maintain alarm zone uncertainty tolerances. Gated amplifiers would be required to prevent processing the aircraft's own transmission due to leakage through the antenna RF-switches, although processing controlled leakage could be used as a self-check for reliability purposes.

The detection portion of the receiver in Figure 18 performs two functions. First, it detects the presence of a binary-one or zero coding in the pulse. Second, it sends all pulses to the evaluator as intruder information. A threshold would have to be established to prevent excessive false alarms due to noise and to minimize the effect of low level multipath signals.

The form of the detector would depend on how the serial binary information was coded from pulse to pulse. It is denoted as being bi-polar in Figure 18 to distinguish its decoding function. For frequency shift keying, the detector could take the form of a frequency discriminator followed by

post detection integration for pulse matching. The bi-polar threshold would sense signal polarity as a binary one or zero and send the bits to the digital decoder. The absolute value circuit would simply be a logical OR-circuit (for on's and zeroes) whose output would be used as intruder information in the evaluator. All of these functions could be easily realized with commercially available, integrated circuit sense comparators and digital logic circuits. Delay as a function of dynamic signal range would have to be controlled in these circuits.

4.6.5 Digital Decoder

The digital decoder develops data, sync, and timing from the binary output of the threshold circuits. Because of the possibility of multi-intruder signals being present, the digital data would have to be gated into the decoder under control of the evaluator tracking loop gates. The evaluator would sense overlapping intruder signals and inhibit the digital data as well as the intruder information from being processed until the intruders resolve themselves.

Digital parity or error correcting codes could be used to detect and/or correct digital data transmissions. However, this would increase the number of bits to be transmitted for a given message, the amount of time to transmit the data, and the cost of equipment. However, some indication of digital data reliability will be necessary. Because range rate is to be used to evaluate intruder velocity, it is possible that a number of redundant messages can be sent while the evaluation process is going on. In this case, single or double parity bits may be sufficient to indicate digital data trouble. In any event, before a proper evaluation of intruder threat can be made, the digital decoder will have to indicate that a complete data word has been received for a given intruder and that the data is valid. Therefore, there will have to be

synchronization between the evaluator and the digital data receiver. This information is indicated in Figure 18 as the SYNC and Parity inputs to the evaluator.

4.6.6 Multi-Intruder Tracking Gates

One of the reasons for developing collision-avoidance systems such as SAVAS is to better utilize airspace in crowded corridors. Therefore, it is very likely that the system will have a number of intruders within a protected aircraft's alarm region at the same time. This is especially true in landing patterns near airports. Because digital data is to be transmitted serially on successive PRF pulses, it will be necessary to separate intruder signals and track them separately. It is also very probable that intruder signals may overlap in time, and, therefore, some provision must be made to treat these cases.

There are a number of ways to mechanize tracking gates. Since the PRF in the SAVAS system is fixed, a tracking and smoothing loop similar to the one shown in Figure 14 appears to be the most economical. Other multivibrators synchronized with smoothed satellite f_1 pulses, when, used with suitable logic gates, could be used to develop minimum and maximum gates.

A digital version of a tracking loop is shown in Figure 19. It consists of an up-counter, a down-counter, and input gating logic. In principle, the up-counter is reset by the satellite f_1 pulse and begins to count. When an intruder pulse occurs, it is first gated by the minimum range and/or the maximum range gates which are developed from the up-counter. If the intruder is within either gate, it transfers the number in the up counter to the down-counter. This number corresponds to the intruder delay. The down-counter holds the number until the next satellite f_1 pulse, at which

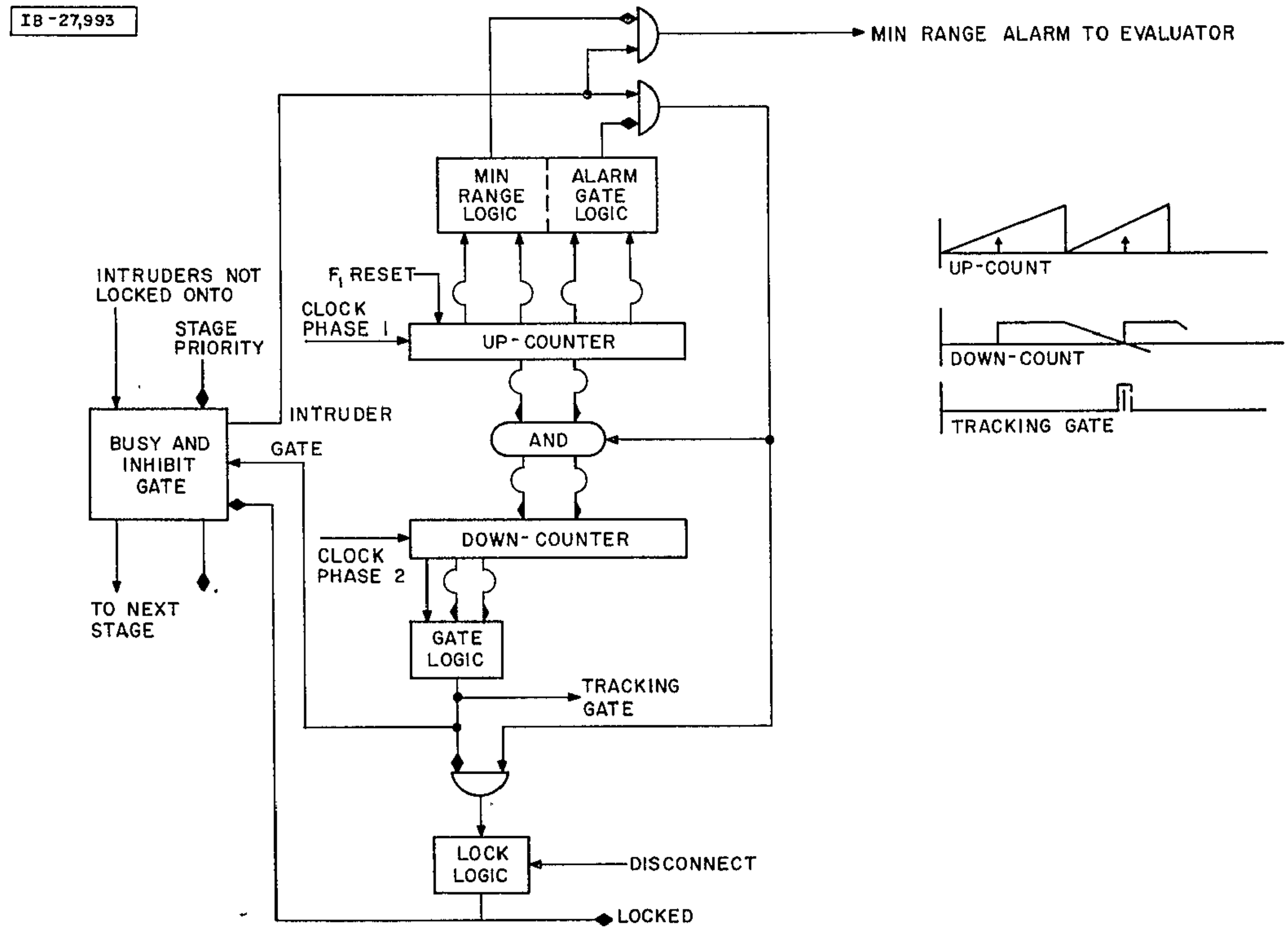


Figure 19. Simplified Block Diagram of a Digital Tracking Gate

time it begins to count down to zero. Gate logic on the down-counter establishes a gate when the count is near zero, and will maintain the gate until an establised time after counter turn-around. The intruder will fall within the gate and repeat the procedure on the next PRF period. After the intruder has been gated a number of times, "lock logic" establishes that it is a true signal and sets up a tracker-locked condition. This condition inhibits the intruder from other trackers by gating it out of the data stream. It also establishes a priority signal to the other trackers so that all trackers do not attempt to lock on to the same signal. The tracker can be designed to maintain lock (flywheel) through missing pulses and will disconnect itself after "too many" missing pulses or on command from a disconnect signal.

The digital tracker has been described in some detail here because it has the potential to be expanded to handle a large number of intruders by placing a digital memory in place of the down-counter and storing intruder time delay in successive memory locations. Then, by successively reading the memory into a down-counter, tracking gates associated with a memory address could be established. The logic for this scheme has not been studied in detail. There are many problems associated with it, and more study is required before applicable trade-off factors can establish it as a practical solution for tracking a large number of intruders.

The problems associated with multi-intruder cross-over and multipath signals on signal tracking are complex. Multipath signals, if they were sufficiently stable, would simply be processed as an intruder. Otherwise, they would be detected, tracked, and lost with the net result of tying-up tracking channels. For signals which cross over, tracking channels may exchange signals (or lose them due to distructive interference), with little consequence provided that the signals were not being evaluated at the same time. In the case where crossing signals were being evaluated the signal

overlap would be detected, and the evaluator would reject the information until the signals resolved themselves. In some situations, a relatively long time may be required before all signals get processed.

Finally, the intruder trackers could be biased to lock-on to the lowest T intruders first. However, low T intruders may not be the greatest threat; a high speed intruder at maximum range may have the least time-to-go to threatened collision.

4.6.7 Alarm Evaluation Multiplexer

It has been established that in order to evaluate intruder collision threat, each of the intruders must be tracked separately. In crowded air-space situations, the number of tracking and evaluation channels may be quite large (no requirements have been designated for this study). While analog tracking channels, such as the one shown in Figure 14, or the digital tracker shown in Figure 17 can be mass-produced at relatively low cost (using monolithic IC technology), the complexity of the T and coaltitude evaluators may increase the required equipment cost an intolerable amount if each tracker has its own evaluator.

Figure 20 shows a simplified diagram of a tracking gate multiplexer. A number of trackers are shown. If it is presupposed that trackers can be disconnected if after evaluation the target presents no hazard, then the number of trackers can be limited according to some queing theory based on maximum expected traffic density. Figure 20 shows only one evaluator for purposes of illustration. Actually, several evaluators could be multiplexed between a large number of tracking channels. The number of tracking channels, the number of evaluators, and the multiplexer complexity trade-off factors require considerable study before the practicality of this idea can be established.

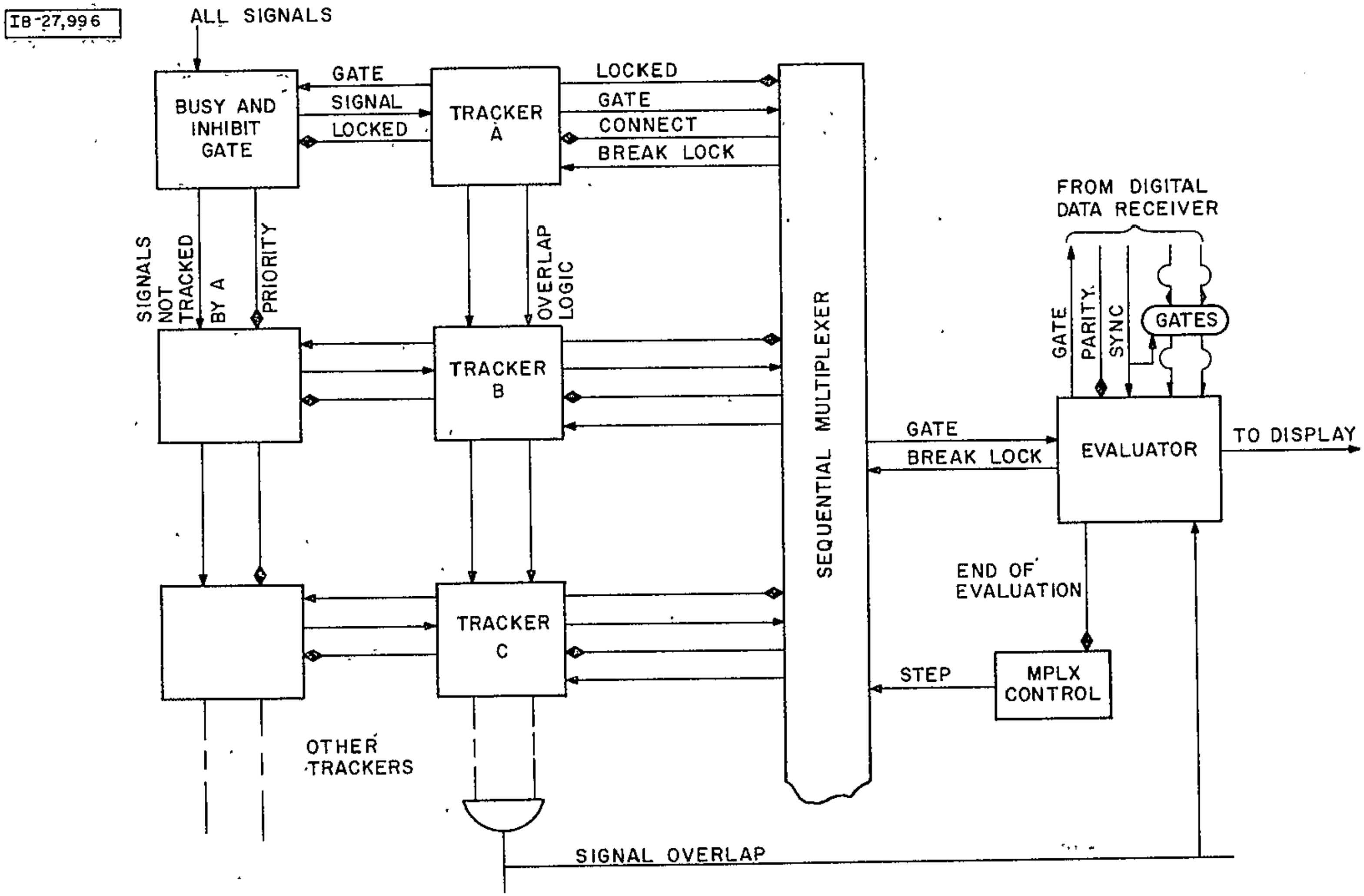


Figure 20. Simplified Block Diagram of Tracking Gate Multiplexer

In any event, the tracking channels should be developed so that they are iterative circuits (that is, outputs can be connected to inputs in an endless cascade). The trackers require input gating and queing logic at their signal inputs so that no two trackers lock on to the same signal. As shown in Figure 20, each tracker must have a locking priority and must also delete the signal it is tracking from those further on in the cascade. In addition, each tracker must send signal overlap logic to every other tracker in the cascade (detailed input and overlap logic in the form of iterative circuits have been designed but the detailed design is not included in this report).

In operation, the multiplexer first senses whether a tracking channel has locked on to a signal. If it has, the channel tracking gate is connected to the evaluator. The connect signal also tests for tracking gate overlap with all other tracking channels. In case of overlap, the multiplexer steps to the next channel. If there is no overlap, the selected tracking-gate gates serial digital data associated with the tracked signal into the digital decoder and thence to the evaluator. The tracking gate is also used to gate the selected signal for τ measurement. When the τ measurement has been completed, and when a valid digital message has been received, the evaluator makes a potential hazard decision. If there is a threat, an alarm is given. If there is no threat, the evaluator sends a break-lock signal to the tracker. In either case, an end-of-evaluation signal is given to step the multiplexer to the next locked channel.

The "no threat" decision can be based on various combinations of altitude difference, absolute delay, opening relative velocity, and τ. By breaking lock with non-threat intruders, and by proper tracker queing so that all delay intervals are covered, only those intruders which are potential hazards continue to be tracked. All other intruders continue to sequence in and out of

evaluation. The multiplexer could also be designed to give priority to, that is, evaluate more often, intruders that are potential hazards.

The minimum SAVAS system that an aircraft would carry would be the satellite receiver and the aircraft-to-aircraft transmitter with the "own" altitude digital encoding and modulator equipment. If some information concerning proximity of other aircraft were required, the aircraft receiver, with delay gating, would offer a proximity warning.

A standard SAVAS system, or any system which requires altitude comparison, would require the full complement of equipment including the trackers, multiplexers, and evaluators described thus far in this Section.

4.6.8 Tau Evaluation

In collision-avoidance systems, the accepted criterion for a collision hazard is when the measured time-to-go to projected collision, generally designated as Tau, drops below a specified value. Tau can be determined by dividing the separation of two aircraft by their relative rate of closure.

In the two-frequency SAVAS system, only an approximation of separation can be obtained (See T in Figure 10). Since the system RF pulses are not coherent, doppler cannot be used to determine rate of closure. In the SAVAS system, $\dot{T}$ contains components of the satellite velocity. Under suitable assumptions, discussed in Section 4 and Appendix III, the difference between $\dot{T}$ and the true relative rate of aircraft closure is small. Such will be the assumption here.

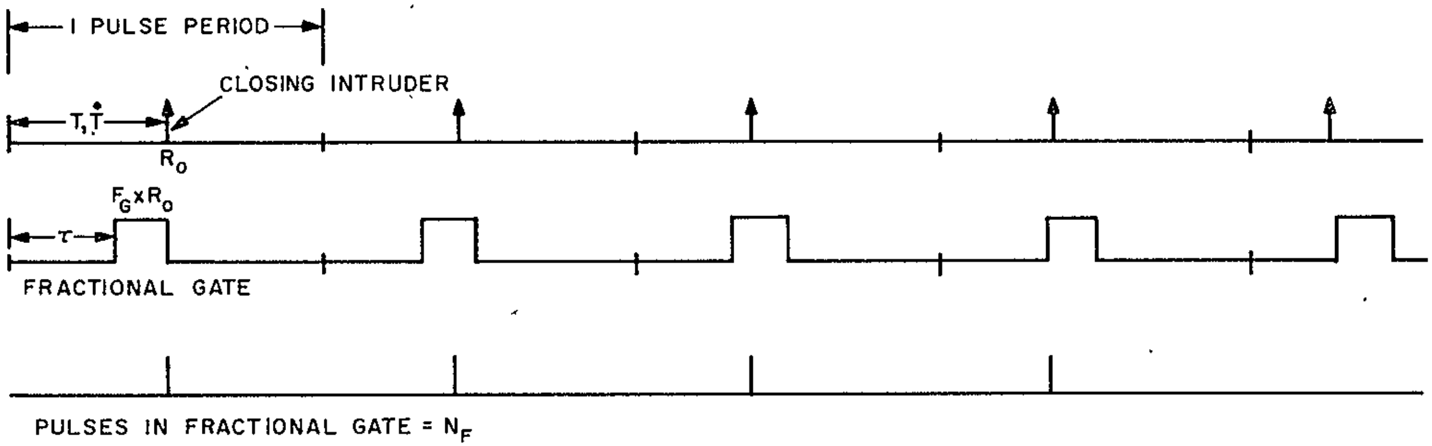
An average value of $\dot{T}$ can be measured by counting how many pulses are received as an intruder passes through a fixed range gate. The value of the accumulated count is directly proportional to the gate width and the PRF, and is inversly proportional to $\dot{T}$. In particular, if the gate-width

is some fixed fraction of the intruder range, the value of the accumulated count will be proportional to Tau. Figure 21 shows an exaggerated version of the operation of a fixed fractional gate. The number of pulses, N_F, is proportional to τ times a constant. In this case, τ is measured when the intruder leaves the gate. The problem is how to implement a gate that is always a fixed fraction of the intruder range and hold the gate position until the intruder passes through it.

It has been suggested (Reference [1]), that a fixed series of exponential gates be established by suitable logic connected to a binary counter. This would be somewhat cumbersome under multi-tracker multiplexing conditions. The intruder could appear anywhere in a given fractional gate, and the intruder would have to transit at least two fractional gates before assurance was made of a correct evaluation. Furthermore, either accumulating counters would have to be connected to each fractional gate, or else one counter would have to be gated to the fractional gate in which the intruder appeared. Either way, considerable logic would be required.

Figure 22 shows a simplified functional diagram of a dynamic fractional gate τ evaluator. This unit establishes a fractional gate at the range of the intruder, holds the gate until the intruder passes through it, and accumulates the Tau count for evaluation. Thus, under multiplexing conditions, the intruder pulse establishes the gate position, and evaluation time is decreased.

The principal of operation is similar to the digital tracking gate discussed in Section 4.6.5. In Figure 22, Counter A counts up until it is reset by the satellite f_1 sync-pulse. When the tracker multiplexer connects a tracking gate to the control unit, the associated intruder pulse is gated by either the minimum range gate or the alarm gate. If the intruder is within either gate, it transfers the number in Counter A to down-Counter B and



$$N_F = \tau \frac{PRF \times F_G}{1 - F_G}$$

Figure 21. Operation of a Fractional Gate

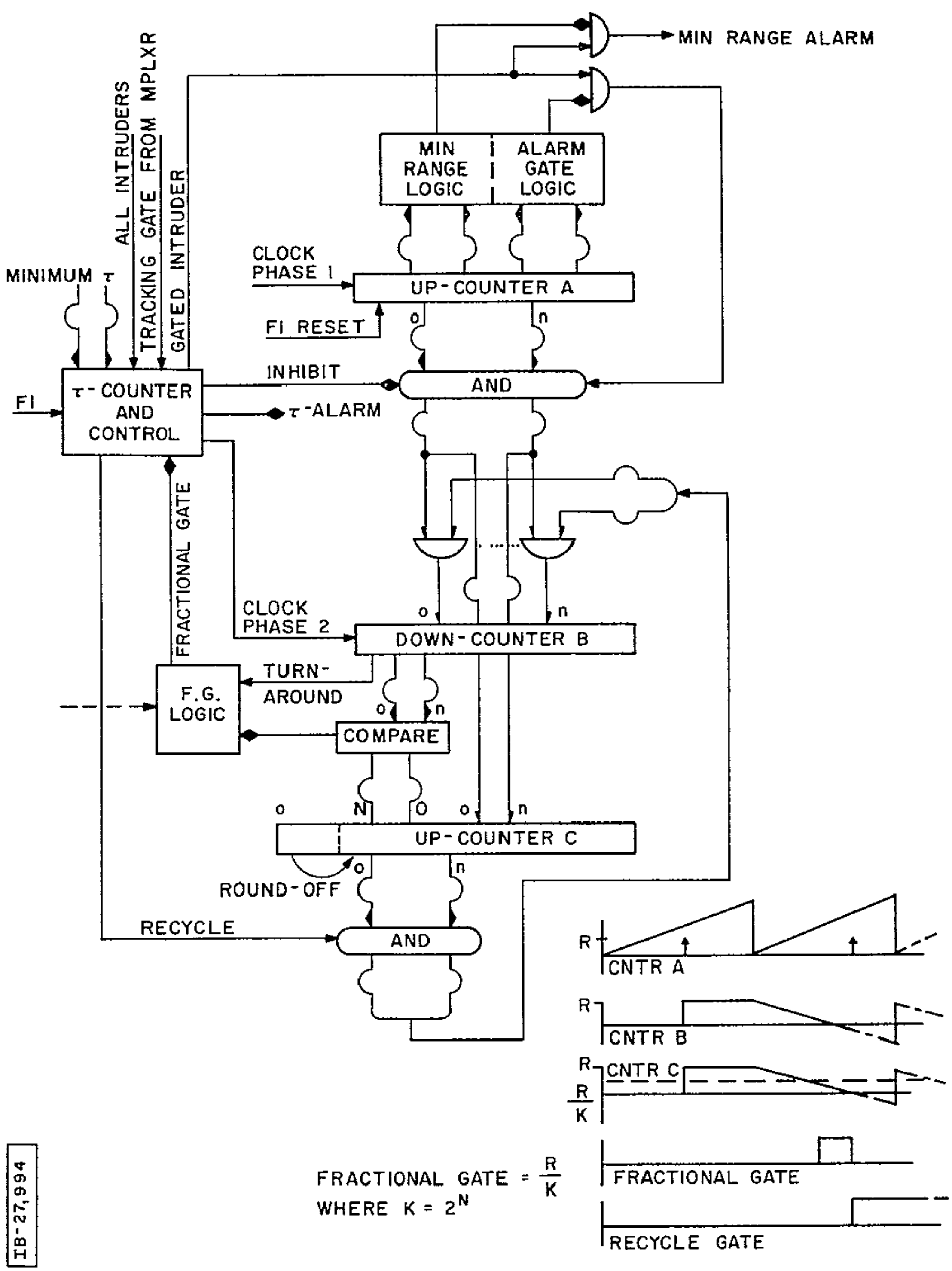


Figure 22. Simplified Functional Diagram of a Dynamic Fractional Gate τ Evaluator

and Counter C. This number corresponds to intruder range, R. The control holds the number until the next satellite f_1 sync pulse, at which time it begins to count down to zero. A digital comparator compares the count in down-counter B to only the first n-N most significant bits of Counter C. This is equivalent to dividing the number in Counter C by a number equal to 2^N. Thus, the gate fraction must be chosen to be an inverse power of two (this is not much of a limitation). When the numbers compare, there are $R/2^N$ counts left in down counter and the fractional gate is started. When counter turn-around occurs (zero count), the gate is stopped. This time period corresponds to intruder range for the previous PRF period. A recycle gate is then established so that the contents of Counter C (which have been left undisturbed) are transferred to down-Counter B and cycle repeats, holding the fractional gate width and position until the intruder pulse passes outside of the gate. The first pulse outside of the gate establishes an evaluation-complete condition. Intruder pulses which have been gated by the fractional gate are accumulated by a τ counter. The count is compared digitaly with a minimum number or numbers, and an alarm decision is made (various numbers could generate alarms of varying degrees).

The case arises where an intruder may establish a fractional gate and then not leave it (no closing rate). This case can be taken care of by allowing τ count overflow to terminate the evaluation. Another case arises where a τ gate is established for enough counts to make it look like a real threat, but the intruder enters and leaves from the same side of the gate. This case can be taken care of by sensing for a complete gate transit. Other cases, such as very slow intruders at long range, can be sensed by τ count overflow, and the evaluation cycle can be terminated before a complete gate transit is made. Tau evaluation time can be decreased in this manner.

Lack of system performance requirements and of time did not permit optimized trade off studes for the PRF, the τ gate fraction, stability, and accuracy. General formulas relating to these subjects are given in Table IV.

Table IV

Summary of Evaluation Formulas

1.	$\tau = \dfrac{N_F (1 - F_G)}{PRF \times F_G}$	τ = Time to go F_G = Fraction of T (Range) N_F = No. of pulses in fractional gate PRF = Rep - rate
2.	$N_F = \tau \dfrac{PRF \times F_G}{1 - F_G} = \dfrac{V}{R} \cdot \dfrac{PRF \times F_G}{1 - F_G}$	V = closing velocity R = Range
3.	The number of pulses in a gate, G, of any length is: $N = 5.82 \dfrac{G \times PRF}{V}$	G = in μ sec V = in hundreds of mi/hr.
4.	Time-to-go in terms of R, V, F_G: $\tau = 35.21 \dfrac{R}{V} (1 - F_G)$ sec.	R = in mi V = in hundreds of mi/hr.
5.	Rate of change $\dot{T}$ in terms of V is: $\dot{T} = 0.172\ V\ \mu \sec/\sec$	V = in hundreds of mi/hr.
6.	1 nautical mile = 6.17 μ sec (one way).	

4.6.9 Alarm Evaluator

Detailed equipment studies of an alarm evaluator would have to be centered on system requirements. Generally, digital comparison logic circuits exist for such measurements as $A < B < C$, where A and C are fixed digital numbers and B is a variable digital number. Inputs to an alarm evaluator can be combined in almost any logical manner to produce display lights or tones.

4.6.10 Alarm Display

Detailed equipment studies of displays for alert signals would have to be centered on system requirements and operational procedures, which are not yet available.

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SECTION 5

THREE-FREQUENCY SAVAS EQUIPMENT CONSIDERATIONS

Time did not permit extensive evaluation of the three-frequency SAVAS system. Power levels should be about the same as for the two-frequency system. However, a cursory look at the increased multipath problems (above those for the two-frequency system) indicates that the three-frequency system may be impractical.

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SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 RESULTS

The primary findings of this review of the SAVAS approach are:

(a) The basic SAVAS concept provides aircraft with alarm indications that give suitable collision warning when normalized for speed of closure and evasive action time.

(b) Preliminary analysis indicates that equipment required to implement the basic concept lies within presently developed technology.

(c) Fundamental system problems exist with regard to large scale utilization of the concept; a number of these problems are identified in this report, and others may also be present. All these problems must be resolved for the SAVAS concept to attain operational candidacy.

(d) At the present stage, it is too early in the conceptual development for meaningful cost estimates to be made.

6.2 INTERPRETATION OF RESULTS

It is clear that assessment of the overall feasibility of the approach requires consideration of the problems remaining and the prospects for their successful resolution. The basic outcome of our evaluation of these factors, and the findings above, is that while the basic concept has been verified, the possibilities of successfully resolving the remaining operational problems and of maintaining economic feasibility do not appear promising. The difficulty of the development task appears to be very formidable. In particular:

(a) All major system problems must be either solved or reduced to negligible importance; the successful utilization of SAVAS can be seriously impaired by inability to cope with any one of the major problem areas. The fact that a significant number of problems exist multiplies the difficulties.

(b) The elements of the SAVAS system are highly interactive, and therefore modifications to alleviate particular problems will almost always have a strong impact on other aspects of performance. Consequently, in most cases, methods for dealing with the problems will be severely constrained.

(c) The cost of the SAVAS approach is uncertain at this point and represents an additional problem area.

It should be emphasized that this assessment is an estimate of probabilities, not an assertion of the impossibility of SAVAS development. It primarily reflects empirical engineering results that are encountered with tasks of what are believed to be similar levels of difficulty.

6.3 RECOMMENDATIONS

In order to be meaningful, any overall recommendations must involve consideration of alternatives that are beyond the scope of this study. For this reason, except for the subject of task priorities in further SAVAS work which does fall within the scope of the study, recommendations have not been treated.

With regard to priorities, it is strongly recommended that the first stage of further SAVAS effort be devoted to the basic system problems of operational utilization. Detailed design and economic trade-off studies should be postponed until most of the system problems are resolved, since equipment requirements cannot be firmly established until then.

APPENDIX I

CALCULATION OF CO-ALTITUDE ALARM REGIONS

By definition, the alarm regions surrounding a protected aircraft are the locus of all points such that,

$$-\frac{T}{\dot{T}} \leq \tau , \quad \dot{T} < 0 . \tag{17}$$

Assuming a two-aircraft encounter, either aircraft may be considered the protected aircraft and the following is true,

$$C\,T = R + D - S ,$$

where

$$R = (\bar{R} \cdot \bar{R})^{1/2} , \quad S = (\bar{S} \cdot \bar{S})^{1/2} , \quad D = \left\{ (\bar{S}-\bar{R}) \cdot (\bar{S}-\bar{R}) \right\}^{1/2} .$$

We now choose a cartesian coordinate system such that,

$\bar{R} = i\,x + j\,y + k\,z = i\,R\,(\cos e \cos a) + j\,R\,(\cos e \sin a) + k\,R\,(\mathrm{Sin}\, e)$

$\bar{S} = i\,S\,(\cos \epsilon \cos \alpha) + j\,S\,(\cos \epsilon \cos \alpha) + k\,S\,(\mathrm{Sin}\, \epsilon)$.

Then

$$D = \left\{ S^2 + R^2 - 2RS \cos \epsilon \cos e \cos (a - \alpha) + \sin \epsilon \sin e \right\}^{1/2} . \tag{18}$$

Let $\qquad A = \cos \epsilon \cos e \cos (a - \alpha) + \sin \epsilon \sin e.$

Then $\qquad D = \left\{ S^2 + R^2 - 2\,RSA \right\}^{1/2} ,$

and

$$C\,T = R + \left\{ S^2 + R^2 - 2\ RSA \right\}^{1/2} - S\ .$$

Solving for R

$$R = \frac{CT\ (S + \frac{CT}{2})}{CT + S\ (1 - A)}\ . \tag{19}$$

This equation defines an ellipsoid of revolution with the protected aircraft at one focus, the satellite at the other focus, and the intruder aircraft at some point on the surface.

Since other means are provided for avoiding collision when the intruder and protected aircraft are at different altitudes, we confine our attention to the co-altitude case. In this case, the elevation angle, e, of the intruder is zero and

$$A = \cos \epsilon \cos\ (a - \alpha)\ .$$

To find the alarm regions surrounding the protected aircraft we now solve the equation

$$-\frac{T}{\dot{T}} = -\frac{R + D - S}{\dot{R} + \mathring{D}} \leq \tau,\ \dot{T} < 0\ , \tag{20}$$

where the assumption is made that the satellite is so far away that $\dot{S}$ may be ignored.

$\dot{R}$ can be obtained by differentiating

$$R = (x^2 + y^2)^{1/2}$$

giving, in terms of the relative heading of the intruder

$$\dot{R} = V \cos (a - h) ,$$

and $\dot{D}$ can be obtained from

$$D = \left\{ S^2 + R^2 - 2\, R\, S\, A \right\}^{1/2}$$

$$\dot{D} = \frac{1}{D} \left\{ R\, V \cos (a - h) - S\, V \cos \epsilon \cos (\alpha - h) \right\} .$$

The quantity $T + \tau \dot{T}$ can then be shown to be equal to

$$T + \tau \dot{T} = \frac{1}{D} \left\{ D\, (R + D - S) + (D + R)\, V \tau \cos (a - h) - V \tau S \cos \epsilon \cos (\alpha - h) \right\} . \tag{21}$$

Without loss of generality, we can now set the relative heading, h, of the intruder equal to π, set the equation equal to zero, and solve for R as a function of a with α and ϵ as parameters.

A great simplification can be made in these equations by assuming that the distance to the satellite is much greater than the distance to the intruder. That is

$$S >> R .$$

We can take the limit of Equation (19)

$$R = \lim_{S \to \infty} \frac{C\,T\,(S + \frac{C\,T}{2})}{C\,T + S\,(1 - A)} = \frac{C\,T}{1 - A}$$

and, again considering the co-altitude case only,

$$R = \frac{C\,T}{1 - \cos\epsilon\,\cos\,(a - \alpha)} \quad . \tag{22}$$

If we now solve the equation

$$- \frac{T}{\dot{T}} \leq \tau$$

the result is

$$R \leq V\,\tau \left\{ \frac{\cos a - \cos\epsilon\,\cos\alpha}{1 - \cos\epsilon\,\cos\,(a - \alpha)} \right\} \quad . \tag{23}$$

where, once again the relative heading of the intruder has been set equal to π.

Equation (23) is plotted in Figures 3 to 7 with the elevation angle, ϵ, and the azimuth angle, α, of the satellite as parameters. The exact equation (21) has been programed for a 7030 computer and the results compared with the values given by Equation (23). The comparison shows that, for satellite distances greater than 1000 km, the error in Equation (23) never exceeds 0.2 percent.

APPENDIX II

RECEIVING GATE LENGTH OR MAXIMUM T CRITERION

Equation (22) gives the range to the intruder

$$R = \frac{C\,T}{1 - \cos\epsilon \cos(a - \alpha)} , \tag{22}$$

and Equation (23) gives the $(T/\dot{T})$ alarm region as

$$R \leq V\tau \frac{\cos a - \cos\epsilon \cos\alpha}{1 - \cos\epsilon \cos(a - \alpha)} \tag{23}$$

If we wish to establish a maximum gate length, T_{max}, beyond which no signals are accepted, this gate length must be at least long enough to receive the signal from an intruder with maximum closing speed on a collision course, using the worst case position of the satellite. A collision course is defined by $a = 0$ and the worst case condition of the satellite position is given by,

$$\epsilon = \epsilon_{min} \quad \text{and} \quad \alpha = \pi ,$$

since this makes the denominator of Equation (22) a maximum. Under the same conditions, Equation (23) shows that

$$R_{max} = V_{max}\,\tau .$$

Then from Equation (22)

$$T_{max} = \frac{R_{max}\,(1 + \cos\epsilon_{min})}{C} = \frac{V_{max}\,\tau\,(1 + \cos\epsilon_{min})}{C} . \tag{24}$$

The range to the intruder when he first penetrates the gate is then

$$R_G = \frac{C\,T_{max}}{1 - \cos\epsilon \cos(a - \alpha)} = \frac{V_{max}\,\tau\,(1 + \cos\epsilon_{min})}{1 - \cos\epsilon \cos(a - \alpha)} \tag{25}$$

$$\frac{\pi}{2} \geq \epsilon \geq \epsilon_{min} \,.$$

It is clear that the gate can never cut off any part of the alarm regions since the denominator of Equations (25) is the same as the denominator of Equations (23) and

$$V_{max}\,\tau\,(1 + \cos\epsilon_{min}) \geq V\,\tau\,(\cos a - \cos\epsilon \cos\alpha)$$

$$\epsilon_{min} \leq \epsilon \leq \frac{\pi}{2} \,.$$

The shape and size of the maximum gate region can be found by noting that Equation (25) is the same as Equation (6) in Section 3 with R_{min} replaced by $V_{max}\,\tau$. Figure 7 is then also a plot of the maximum gate when the scales are multiplied by $V_{max}\,\tau\,(1 + \cos\epsilon_{min})$. The same remarks concerning orientation of the Figure apply.

APPENDIX III

EFFECTS OF SATELLITE VELOCITY

In Appendix I it is shown that when the satellite is sufficiently far away, the warning regions can be calculated with negligible error by assuming the satellite to be at an infinite distance. An even more important reason for restricting the satellite distances to large values is the effect that satellite motion produces on the measurement of $\dot{T}$.

In Figure 23, $\overline{V}_s$ is the vector velocity of the satellite, with respect to the protected aircraft, θ the angle that $\overline{V}_s$ makes with the line of sight to the protected aircraft, and φ the angle between the lines of sight to the protected aircraft and intruder aircraft.

From Appendix I

$$C\dot{T} = \dot{R} + \dot{D} - \dot{S} .$$

If we assume that $\dot{R}$ is zero then

$$C\dot{T} = \dot{D} - \dot{S} .$$

We can now write (see Figure 23)

$$\dot{S} = V_s \cos\theta , \quad \dot{D} = V_s \cos(\theta + \varphi) = V_s (\cos\theta\cos\varphi - \sin\theta\sin\varphi),$$

and

$$C\dot{T} = V_s (\cos\theta\cos\varphi - \sin\theta\sin\varphi - \cos\theta).$$

For satellite distances greater than 1000 km, the angle φ will be small. Cos φ is well approximated by unity and sin φ may be replaced by φ. Then

$$C\dot{T} = - V_s \varphi \sin\theta .$$

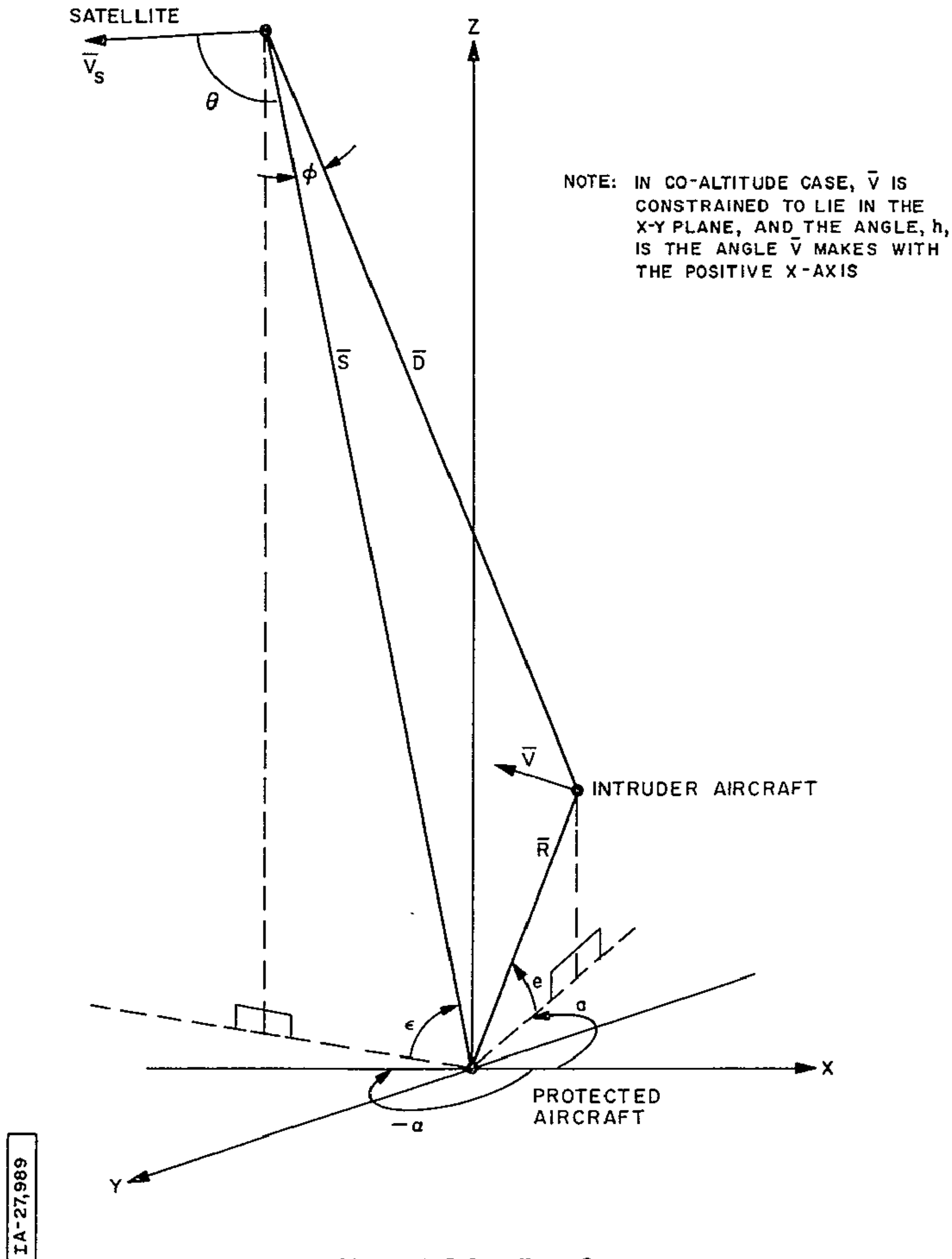

Figure 23. SAVAS Coordinate System

The largest value of φ are attained when the intruder and satellite positions are such as to form an isosceles triangle. Then φ may be approximated by R/S and

$$C\dot{T} = -\frac{V_s R}{S} \sin\theta .$$

When θ is small, that is, where the satellite velocity in nearly parallel to the line of sight to the satellite, the effect on $\dot{T}$ is negligible. However, when θ is nearly $\pi/2$, $C\dot{T}$ due to satellite velocity may become as high as

$$C\dot{T} = -\frac{V_s R}{S}$$

and this can be a significant quantity unless S is very large. For example, assume a satellite distance of 1000 km, an intruder range of 20 km and a satellite speed of 6 km per second. Then

$$C T = -\frac{20}{1000} 6000 = -120 \text{ meters per second.}$$

Since θ can be either $\pi/2$ or $-\pi/2$ depending on the direction of satellite motion, this value of $C\dot{T}$ can either add to or subtract from the component of $C\dot{T}$ caused by relative motion between protected aircraft and intruder.

Greater satellite distances will reduce the effect of satellite velocity not only by increasing the value of S, but also by tending to make V_s smaller. For example, a satellite at synchronous distance, on the equator, will have no relative velocity with respect to the surface of the earth, and thus V_s will be simply the velocity of the protected aircraft.

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